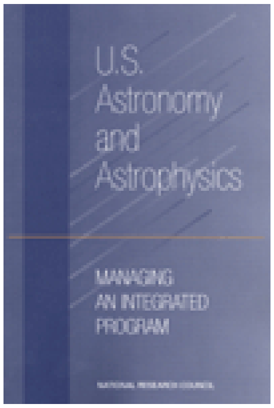

U.S. Astronomy and Astrophysics: Managing an Integrated Program

Committee on the Organization and Management of Research in Astronomy and Astrophysics, National Research Council

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U.S. Astronomy and Astrophysics

MANAGING AN INTEGRATED PROGRAM

Committee on the Organization and Management of Research in
Astronomy and Astrophysics

National Research Council

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Preface

In its fiscal year 2002 budget summary document[1] the Bush administration proposed funding initiatives and redirections for each department and agency, and it also discussed potential reforms. For the National Science Foundation (NSF), the potential reforms included a directive to "reorganize research in astronomy and astrophysics." The document (p. 161) added:

> Several changes have evolved which suggest that now is the time to assess the federal Government's management and organization of astronomical research. NSF and NASA will establish a Blue Ribbon Panel to assess the organizational effectiveness of Federal support of astronomical sciences and, specifically, the pros and cons of transferring NSF's astronomy responsibilities to NASA. The panel may also develop alternative options.

In response to a request from the director of NSF and the administrator of NASA, the National Research Council (NRC) agreed to undertake preparation of the assessment. The NRC chair appointed the Committee on the Organization and Management of Research in Astronomy and

[1]Executive Office of the President, *A Blueprint for New Beginnings: A Responsible Budget for America's Priorities*, U.S. Government Printing Office, Washington, D.C., 2001. Available online at <http://www.whitehouse.gov/news/usbudget/blueprint/budtoc.html>.

Astrophysics (COMRAA) to carry out the task. Biographies of the members of the committee are given in Appendix A.

The committee was formally charged with the following task, based closely on the language in the 2002 budget summary.

1. Assess the organizational effectiveness of federal support of astronomical sciences.
2. Discuss the advantages and disadvantages of transferring NSF's astronomy responsibilities to NASA.
3. Consider other options for addressing the management and organizational issues identified by the committee and by recent NRC reports.

COMRAA met in person three times for a total of six days and held one telephone discussion. At its first meeting, held in Washington, D.C., on June 13-14, 2001, it heard from representatives of the White House, the sponsoring agencies, and the House Science Committee. It also heard presentations from one of the co-chairs of the recently published survey of astronomy and astrophysics (*Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001), from professional societies, and from other interested organizations and knowledgeable individuals.

At its second meeting, held in Menlo Park, Calif., on July 12-13, 2001, it discussed national observatories and joint advisory committees and heard further testimony from the National Science Foundation and the Department of Energy. The report was outlined and the committee divided up the task of preparing various sections of its report.

During these first two meetings, the committee heard testimony from about 30 key individuals. Committee members also benefited from many individual discussions with senior researchers, congressional staff members, and former and current agency managers. The NRC created a Web site that invited public comment through an e-mail address created for that purpose. The American Astronomical Society assisted the committee by transmitting a general invitation to its membership to submit statements to the committee by e-mail. The committee received hundreds of thoughtful statements and comments that were carefully reviewed during the first two meetings.

At its final meeting, held in Washington, D.C., on July 31-August 1, 2001, the committee, after much discussion, finalized its findings and recommendations. Detailed agendas of the meetings are listed in Appendix B.

The committee wishes to thank NASA Administrator Daniel S. Goldin and NSF Director Rita Colwell and their staffs for providing data and information to the committee, always under tight schedule constraints.

The committee would also like to express its appreciation for the support and assistance of the NRC staff, including the deadline-paced editorial work of Susan Maurizi. The committee particularly thanks Joel Parriott, who served as study director, and without whose help and guidance the committee could not have completed its task on the fast-paced schedule dictated by the budget cycle.

The recommendations presented in this report have the unanimous endorsement of the members of the committee.

Norman R. Augustine, *Chair*
Committee on the Organization and Management of
Research in Astronomy and Astrophysics

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Robert A. Frosch, Harvard University,
John P. Huchra, Harvard-Smithsonian Center for Astrophysics,
John C. Mather, NASA's Goddard Space Flight Center, Infrared Astrophysics Branch,
Marcia K. McNutt, Monterey Bay Aquarium Research Institute,
Norine E. Noonan, National Space Science and Technology Center,
Jeremiah P. Ostriker, Princeton University,
John Peoples, Jr., Fermi National Accelerator Laboratory,
Marcia J. Rieke, University of Arizona,
Philip M. Smith, McGeary and Smith, and
Joseph H. Taylor, Jr., Princeton University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Marshall Cohen, California Institute of Technology, and Louis J. Lanzerotti, Bell Laboratories, Lucent Technologies. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Executive Summary

In its fiscal year 2002 budget summary document[1] the Bush administration expressed concern—based in part on the findings and conclusions of two National Research Council studies[2]—about recent trends in the federal funding of astronomy and astrophysics research. The President's budget blueprint suggested that now is the time to address these concerns and directed the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) to establish a blue ribbon panel to (1) assess the organizational effectiveness of the federal research enterprise in astronomy and astrophysics, (2) consider the pros and cons of transferring NSF's astronomy responsibilities to NASA, and (3) suggest alternative options for addressing issues in the management and organization of astronomical and astrophysical research. NASA and NSF asked the National Research Council to carry out the rapid assessment requested by the President. This report, focusing on the roles of NSF and NASA, provides the results of that assessment.

Overall, the federal organizations that support work in astronomy and astrophysics manage their programs effectively. These programs

[1]Executive Office of the President, *A Blueprint for New Beginnings: A Responsible Budget for America's Priorities*, U.S. Government Printing Office, Washington, D.C., 2001.

[2]The two National Research Council reports are *Federal Funding of Astronomical Research* (2000) and *Astronomy and Astrophysics in the New Millennium* (2001), National Academy Press, Washington, D.C.

have enabled dramatic scientific progress, and they show excellent promise of continuing to do so. Nonetheless, the existing management structure for the U.S. astronomy and astrophysics research enterprise is not optimally positioned to address the concerns posed by the mounting changes and trends that will affect the future health of the field.

The existing management structure for astronomy and astrophysics research separates the ground- and space-based astronomy programs. NSF has responsibility for the former and NASA has responsibility for the latter. The ground-based optical/infrared observatories funded by private and state resources constitute an important third component of the system. In astronomical and astrophysical research, NASA's strength has been the support of work related to major space missions. NSF's strength in astronomy and astrophysics has been the support of a broad spectrum of basic research motivated by the initiative of individuals and small groups in the scientific community and by its role in assuring the continued availability of broadly educated scientists. The NSF also funds research in related fields such as physics, geophysics, computation, chemistry, and mathematics, providing a broad multidisciplinary context for astronomy and astrophysics research that can promote productive connections among these fields.

Three important changes have occurred in the field over the last two decades. First, ground- and space-based research activities have become increasingly interdependent as well as increasingly reliant on large facilities, major missions, and international collaborations. Second, NASA's relative role in astronomy and astrophysics research has grown markedly. (In 1980, most of the research grants in the fields of astronomy and astrophysics were provided by NSF. Today, most of the grants are provided by NASA.)[3] And third, large state-of-the-art optical/infrared telescopes built with non-federal funds now dominate this component of ground-based astronomy.

These changes necessitate systematic, comprehensive, and coordinated planning in order to sustain and maximize the flow of scientific benefits from the federal, state, and private investments that are being made in astronomy and astrophysics facilities and missions. The increasing financial and intellectual demands to be met by more than one nation in supporting large projects, particularly on the ground, require that the United States develop a unified planning and execution structure to effectively participate in such international ventures. To develop the needed integrated and comprehensive strategy for the field, the committee rec-

[3]This trend was noted in *Federal Funding of Astronomical Research*.

ommends the formation of an interagency planning board for astronomy and astrophysics.

The Committee on the Organization and Management of Research in Astronomy and Astrophysics was charged to consider, among other options, moving NSF's astronomy responsibilities to NASA.[4] Such a move would consolidate the bulk of the federal programs[5] in a single agency and, to some degree, integrate space- and ground-based astronomy. The committee concluded, however, that moving NSF's astronomy and astrophysics activities to NASA would have a net disruptive effect on scientific work. Because of its combined commitment to investigator-initiated research, interdisciplinary research, and educating the scientists of the future, NSF is the right institution to sponsor ground-based astronomy and astrophysics. And further, such a move would not necessarily address integration of the third component of the system (i.e., the ground-based optical/infrared private and state observatories). NSF's close working relationship with the college and university community makes it the natural focus for integration of this third component. The committee's recommendations address improving the present overall management structure, as well as strengthening NSF's ability to support ground-based astronomy and astrophysics and to work effectively in conjunction with the other two primary components of the system. The committee's detailed recommendations are contained in Box ES.1.

In Chapter 1 the committee discusses the discipline of astronomy and astrophysics and the role of the periodic self-assessments carried out by the community.[6] Chapter 2 summarizes the roles and responsibilities of NASA and NSF and discusses some key aspects of their missions, pro-

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[4]It would be unreasonable to consolidate under NSF, i.e., to place space missions under NSF, since NSF has no space experience, does not operate its own facilities, and does not have a large enough budget to carry out space missions.

[5]Additional important federal components include the Department of Energy, which conducts research in particle, high-energy, nuclear, and plasma physics and in computational science related to astronomy and astrophysics; the Smithsonian Institution, which plays a significant role in astronomy and astrophysics research through the Smithsonian Astrophysical Observatory; and the Department of Defense, which supports research in areas such as solar physics, astrometric astronomy, and observing technology that is carried out primarily through multiple programs in the Navy and Air Force research offices.

[6]The latest of these decadal self-assessments conducted by the National Research Council is *Astronomy and Astrophysics in the New Millennium* (National Academy Press, Washington, D.C., 2001). The reports of the seven discipline panels established under the Astronomy and Astrophysics Survey Committee are forthcoming in a companion volume titled *Astronomy and Astrophysics in the New Millennium: Panel Reports* (National Academy Press, Washington, D.C., 2001).

BOX ES.1 Recommendations of the Committee

1. The National Science Foundation's astronomy and astrophysics responsibilities should not be transferred to NASA.
2. In order to maximize the scientific returns, the federal government should develop a single integrated strategy for astronomy and astrophysics research that includes supporting facilities and missions on the ground and in space.
3. To help bring about an integration of ground- and space-based astronomy and astrophysics, the Office of Science and Technology Policy and the Office of Management and Budget should take the initiative to establish an interagency planning board for astronomy and astrophysics. Input to the planning board from the scientific and engineering community should be provided by a joint advisory committee of outside experts that is well connected to the advisory structures within each agency.
   —The recommended interagency Astronomy and Astrophysics Planning Board, with a neutral and independent chair to be designated by the Office of Management and Budget in conjunction with the Office of Science and Technology Policy, should consist of representatives of NASA, NSF, the Department of Energy, and other appropriate federal agencies such as the Smithsonian Institution and the Department of Defense. The Planning Board should coordinate the relevant research activities of the member agencies and should prepare and annually update an integrated strategic plan for research in astronomy and astrophysics, addressing the priorities of the most current National Research Council decadal survey of the field in the context of tight discretionary budgets.
   —The membership of the Planning Board's advisory committee should be drawn in part from the external advisory panels of the Planning Board's member agencies. The advisory committee should be chaired by an individual who is neither a member of the agency advisory panels nor an agency employee. The committee should participate in the development of the integrated strategic plan and in the periodic review of its implementation.
4. NASA and NSF should each put in place formal mechanisms for implementing recommendations of the interagency Astronomy and Astrophysics Planning Board and integrating those recommendations into their respective strategic plans for astronomy and astrophysics. Both agencies should make changes, as outlined below, in order to pursue effective roles in formulating and executing an integrated federal program for astronomy and astrophysics. These changes should be coordinated through the interagency Planning Board to clarify the responsibilities and strategies of the individual member agencies.
5. The NSF, with the active participation of the National Science Board, should:
   a. Develop and implement its own strategic plan, taking into account the recommendations of the interagency Planning Board. Its strategic plan should be formulated in an open and transparent fashion and should have concrete objectives and time lines. NSF should manage its program in astronomy and astrophysics to that plan, ensuring the participation of scientifically rel-

evant divisions and offices within NSF. To help generate this plan, NSF should reestablish a federally chartered advisory committee for its Astronomical Sciences Division to ensure parity with the NASA advisory structure. The chair of this Astronomical Sciences Division advisory committee should be a member of the Mathematical and Physical Sciences Directorate advisory committee. Furthermore, the Mathematical and Physical Sciences Directorate advisory committee should make regular written and oral reports of its key findings and recommendations to the National Science Board.

b. Address the outstanding issues that are affecting ground-based astronomy at present.
   - —Lead the development of an integrated strategy for assembling the resources needed to build and operate the challenging suite of ground-based initiatives recommended by the most current decadal survey.
   - —Work to create an integrated system for ground-based optical/infrared astronomy and astrophysics encompassing private, state, and federally funded observatories, as advocated by the decadal survey.
   - —Improve and systematize the process for initiating, constructing, managing, and using ground-based facilities, so that it includes:
     - clear lines of authority for negotiations, particularly those involving international partners,
     - an open bidding process for contracts,
     - comprehensive budgeting that provides for all aspects and phases of projects, and
     - provision of the resources required to exploit the scientific potential of the facilities, including associated instrumentation, theoretical work, data analysis, and travel.

c. Undertake a more concerted and well-funded effort to inform the press and the general public of scientific discoveries, and cooperate with NASA in developing a coordinated public information program for astronomy and astrophysics.

6. In parallel, NASA should:
   a. Implement operational plans to provide continuity of support for the talent base in astronomy and astrophysics should critical space missions suffer failure or be terminated.
   b. Continue and enlarge its program of research support for proposals from individual principal investigators that are not necessarily tied to the goals of specific missions.
   c. Support critical ground-based facilities and scientifically enabling precursor and follow-up observations that are essential to the success of space missions. Decisions on such support should be considered in the context of the scientific goals articulated in the integrated research plan for astronomy and astrophysics.
   d. Cooperate with NSF in developing a coordinated public information program for astronomy and astrophysics.

gram management approaches, and planning processes. Chapter 2 also describes the need for more cooperation and coordination between these two primary funding agencies for the discipline, and it mentions a few related issues that affect the implementation of the recommendations that arise from the community's self-assessments. Chapter 3 specifically addresses the advantages and disadvantages of moving NSF's astronomy and astrophysics responsibilities to NASA. In Chapter 4 the committee presents its findings and recommendations. Committee biographies, meeting agendas, detailed funding and organization data, and a glossary and acronym list are included as appendixes.

1

Astronomy and Astrophysics at the Start of the New Millennium

ASTRONOMICAL AND ASTROPHYSICAL RESEARCH—THE PAST, PRESENT, AND FUTURE

The fields of astronomy and astrophysics are experiencing an extraordinary period of scientific progress. Researchers and the general public are sharing in a steady stream of new discoveries and theoretical advances on such topics as the origin of solar activity, the formation of planetary systems, the character of black holes, and the origin and large-scale structure of the universe (see Box 1.1). These developments stem largely from the availability of new facilities in space and on the ground (and some underground), rapidly advancing computational capabilities, and an active community of scientists in universities, research institutes, and government and other laboratories in the United States, and in their counterparts across the world.

Astronomy and astrophysics have changed profoundly in recent years, as has science generally. Increasingly, important discoveries are made at the interfaces between disciplines, through the use of complementary tools and the computational resources made possible by advanced supercomputers, and through both space- and ground-based facilities operating at disparate wavelengths. Indeed, the once separate identities of ground- and space-based astronomy are almost a thing of the past as researchers increasingly use the tools and data from both venues in concert. Astrophysicists are even increasingly using, or planning to use, new windows onto the universe such as gravity waves and neutri-

BOX 1.1 Some Highlights of Discoveries of the 1990s in Astronomy and Astrophysics

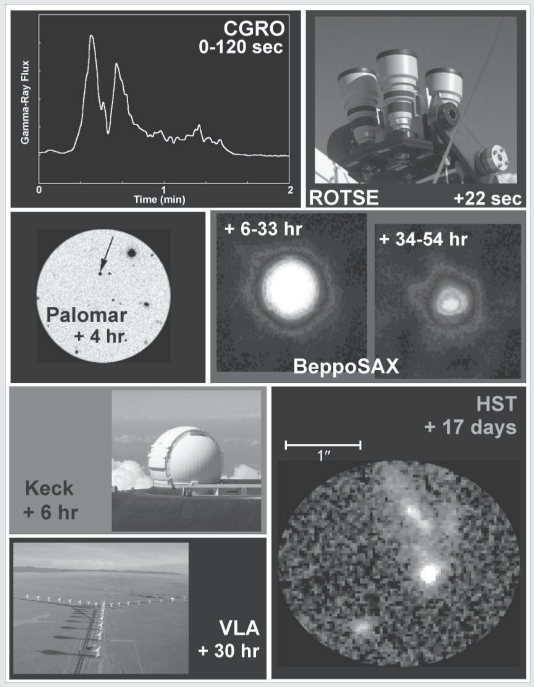
- Discovery of planets orbiting other stars
- Determination of the interior structure of the sun from observations of its seismic activity
- Discovery of Kuiper Belt objects, a large group of small, primitive bodies in the outer solar system
- Observation of the impact of Comet Shoemaker-Levy 9 on Jupiter
- Discovery of "brown dwarfs," cool stars too small to sustain nuclear reactions in their centers
- Discovery of gravitational microlensing of the light of background stars by intervening objects of stellar mass
- Discovery that gamma-ray bursts originate in the very distant universe
- Discovery of massive black holes in the nuclei of galaxies, including our own Milky Way
- Discovery of young galaxies at redshifts greater than 3, revealing the dramatic evolution of galaxies from the early universe to the present
- Discovery of theoretically predicted tiny fluctuations in the background radiation left over from the big bang, the seeds of subsequent structure formation
- Measurement of the expansion rate of the universe to an accuracy near 10 percent and determination that there is not enough matter to stop the expansion of the universe
- Evidence suggesting both that the universe is "flat" and that its expansion is accelerating owing to the presence of "dark energy"

SOURCE: Adapted from National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, pp. 18-19. For nearly every discovery, both NSF and NASA supported the U.S. researchers who used both ground- and space-based facilities, and for some the Department of Energy provided key support as well.

nos. One remarkable aspect of the major discoveries listed in Box 1.1 is the fact that both ground- and space-based observations played important roles in practically every breakthrough, and this trend is expected to increase. The process of identifying the likely sources of cosmic gamma-ray bursts (Box 1.2) provides a good example of the synergy and interdependence between space and ground observing techniques.

Similarly, contemporary astronomy and astrophysics cannot be parsed by wavelength, by the location of the observing instruments, or by nationality. For example, Box 1.3 describes some of the science that will be enabled by the complementary nature of three future international facilities—the Next Generation Space Telescope, the Giant Segmented Mirror Telescope, and the Atacama Large Millimeter Array—that will observe the universe at different wavelengths and from the ground and in

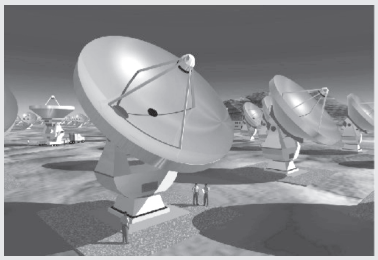
BOX 1.2 Gamma-Ray Burst Imaging



Large advances in understanding gamma-ray bursts have been made possible by the wide variety of facilities available to observe them. The utility of these numerous facilities is best shown using a recent example. On January 23, 1999, the orbiting Compton Gamma-Ray Observatory (CGRO) discovered a gamma-ray burst. The associated optical burst was then observed 22 seconds later by the Robotic Optical Transient Search Experiment (ROTSE). Following that, BeppoSAX detected the x-ray emissions from the event. These observations, especially those by BeppoSAX, allowed astronomers at the Palomar Observatory to determine the precise location of the event, and observers used the Keck telescope in Hawaii to determine the distance and spectrum. Less than a day later, the Very Large Array (VLA) in New Mexico was used to image the afterglow of the event, and 17 days after that the Hubble Space Telescope (HST) finished recording the burst by imaging the galaxy in which it occurred. To date, this is the highest-energy gamma-ray burst ever recorded. Without the wide variety of ground and space instruments available to observe the event much less would have been learned about the nature of these phenomena.

SOURCE: Based on image and caption from Figure 2.10 of National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, pp. 74-75.

BOX 1.3 The Complementary Nature of NGST, GSMT, and ALMA



Three state-of-the-art telescopes are on the horizon: the Next Generation Space Telescope (NGST), the Giant Segmented Mirror Telescope (GSMT), and the Atacama Large Millimeter Array (ALMA). When completed, NGST and GSMT will dramatically enhance astronomers' ability to see faint objects at optical/infrared wavelengths, ranging from galaxies with redshifts over 3 at the edge of the visible universe to Kuiper Belt objects in our own solar system, as well as provide a clearer picture of objects at the limit of the resolving powers of the Hubble Space Telescope or the Keck Observatory. Much as the Keck telescopes and the Hubble Space Telescope work together at present, the NGST and GSMT are expected to complement each other's observations. NGST will be able to image extremely faint objects at optical and infrared wavelengths. The 30-meter GSMT will use its high spatial and spectral resolution and much larger collecting area to probe much more extensively the discoveries made by the NGST. In addition, the GSMT will be easily upgradable to take advantage of new observational technologies. ALMA, by contrast, will image the "unseen" counterparts to objects that NGST and GSMT will observe, detecting the cool radiation that dominates our universe and is observable only at millimeter and submillimeter wavelengths. ALMA images will probe the veils of obscuring dust to reveal aspects of Kuiper Belt objects, new planetary systems, forming stars, and young galaxies at high redshift that are hidden even from the view of NGST and GSMT. Combined with NGST and GSMT, ALMA will help to provide a cradle-to-grave picture of our universe that will be unprecedented. Together these instruments will be more valuable than the three would be if each were functioning on its own.

SOURCE: Images courtesy of NASA's Goddard Space Flight Center (top right; NGST), the Association of Universities for Research in Astronomy, Inc. (center right; GSMT), and the European Southern Observatory (top left; ALMA).

space. As with other areas of science, the increasingly large scale of the tools necessary to address the compelling scientific challenges at the forefront of astronomy and astrophysics reflects a major change in the way the science is conducted in the United States and around the world. The increased reliance on large multinational projects requires a stronger, more unified planning and execution structure in the United States, so that the United States can enter into international agreements[1] from a position of both intellectual and organizational strength.

While astronomical and astrophysical research has much in common with research efforts in other scientific fields in the United States, there are three attributes of the astronomy and astrophysics enterprise that are important to note in the context of this report. First, the key infrastructure upon which astronomers rely comprises two categories of observing tools, namely, ground- and space-based telescopes. The current federal responsibility for support of those two kinds of observing systems is largely the responsibility of two agencies—NSF for ground-based systems and NASA for space-based systems—with several other agencies (Department of Energy, Smithsonian Institution, and Department of Defense) playing important but smaller roles (see Figure 1.1).[2] Second, in contrast with many other areas of physical science, a number of privately sponsored and state-funded observatories play a significant role or even, in the case of optical/infrared astronomy, a dominant role in the U.S. ground-based astronomy and astrophysics enterprise. This direct private sponsorship of major new telescopes for professional research is a testament to the general popularity of astronomy and astrophysics. Third, even though astronomy is becoming a field of large facilities, the typical size of observational collaborations in astronomy remains relatively small—with groups typically consisting of 5 to 10 people or fewer. Consequently, individual initiative within the community plays a significant role in setting the investigator-initiated aggregate scientific program carried out at observatories on the ground and in space.

PLANNING FOR FUTURE PROGRESS

The astronomy and astrophysics community has a unique 50-year tradition of surveying the status of the field at 10-year intervals and set-

[1]For a discussion of such international agreements, see the National Research Council report *U.S.-European Collaboration in Space Science* (National Academy Press, Washington, D.C., 1998).

[2]The federal funding system for astronomy and astrophysics is discussed briefly in Appendix C.

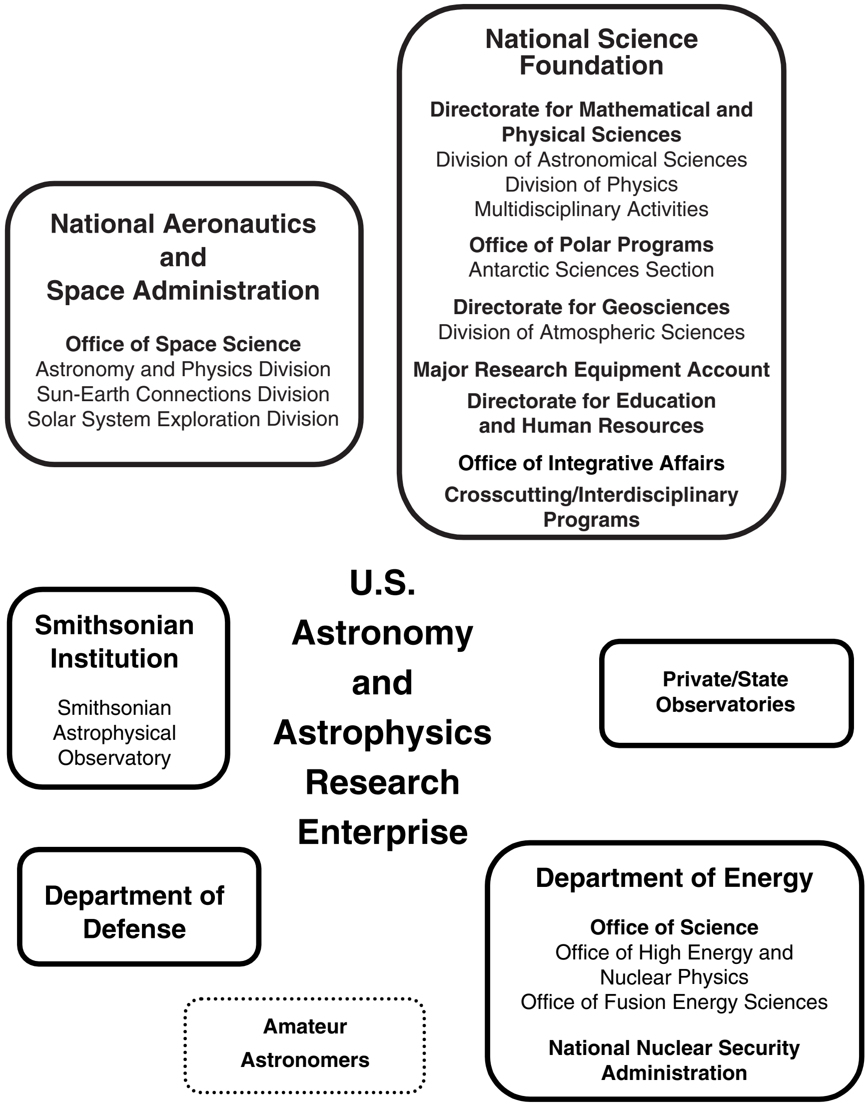


FIGURE 1.1 A schematic representation of the important multiple federal and non-federal elements of the U.S. astronomy and astrophysics research enterprise. The sizes of the individual boxes are not intended to convey any information about the amount of research funding provided by that element. While amateur astronomers participate in some aspects of professional research, they do not directly fund professional astronomers to do research. For more details, see Appendix C in the current report and *Federal Funding of Astronomical Research* (National Academy Press, Washington, D.C., 2000).

ting consensus priorities for the recommended scientific and programmatic directions of the field for the next decade.[3] The preparation of these surveys involves a significant fraction of the astronomy and astrophysics community. Each of the surveys has set ambitious targets for both the community and their federal sponsors, and these survey reports have been remarkably successful in providing blueprints for use by decision makers in the Executive Branch and Congress. Scientists and scientific organizations around the world also use the survey reports as benchmarks for future trends in the field.

The conclusions and recommendations of the most recent survey report (*Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001), together with a companion NRC report that examined recent trends in the funding and demographics for astronomical and astrophysical research (*Federal Funding of Astronomical Research*, National Academy Press, Washington, D.C., 2000), have important implications in the context of this study. These two reports raised concerns that in spite of the vigorous pace of scientific developments in contemporary astronomy and astrophysics, there are warning signals and trends that require attention if the field is to continue on this productive path well into the future. These trends were, to a large degree, what prompted the call for potential reform in the Bush administration budget blueprint.[4] It is these issues that the current study attempts to address.

Issues Discussed in Recent National Research Council Assessments of the Discipline

Federal Funding Study

The National Research Council report *Federal Funding of Astronomical Research* (National Academy Press, Washington, D.C., 2000) found that over the last two decades, the balance of research grant support has shifted away from NSF and toward NASA. The report attributed most of this

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[3]These five National Research Council survey reports, published initially by the National Academy of Sciences and later by the National Academy Press in Washington, D.C., are *Ground-based Astronomy: A Ten-Year Program* (1964), *Astronomy and Astrophysics for the 1970's* (1972), *Astronomy and Astrophysics for the 1980's. Volume I: Report of the Astronomy Survey Committee* (1982), *The Decade of Discovery in Astronomy and Astrophysics* (1991), and *Astronomy and Astrophysics in the New Millennium* (2001).

[4]Executive Office of the President, *A Blueprint for New Beginnings: A Responsible Budget for America's Priorities*, U.S. Government Printing Office, Washington, D.C., 2001.

trend to a significant increase in research grants connected to astronomy and astrophysics missions launched by NASA during a time when growth in funding for NSF astronomy research grants was barely keeping pace with inflation. (This increase in astronomy and astrophysics research grants at NASA was due largely to the integrated research programs of the flagship missions, or so-called Great Observatories—the Hubble Space Telescope, Compton Gamma-Ray Observatory, Chandra X-ray Observatory, and Space Infrared Telescope Facility.) In particular, NSF's share of federal support for grants to researchers in the discipline fell from 60 percent at the beginning of the 1980s to 30 percent at the end of the 1990s.

The report found that this shift had produced imbalances—for example, funding for broad-based astrophysical theory has not kept pace with the research funding for the field as a whole. And it found that the number, size, and capability of ground-based observing facilities have increased considerably without a commensurate increase in NSF funds for utilizing the facilities. The report suggested including in the plan for each new initiative a strategy for accomplishing its scientific mission. It identified a number of elements that should be included in the strategy, among them funds for enabling instrumentation, for observations and analysis, and for theoretical studies. Finally, the report observed that much of the support of astronomy and astrophysics is now tied to a few flagship NASA missions, making the research community vulnerable to a catastrophic failure of one of these large missions.

Decadal Survey Report

The most recent decadal survey prepared under the auspices of the National Research Council is *Astronomy and Astrophysics in the New Millennium* (National Academy Press, Washington, D.C., 2001). The report begins with a proposed scientific program for the next decade, describes the ground- and space-based facilities necessary to achieve that program, and then discusses policy recommendations relevant to the current and future health of the field.

The ambitious overarching scientific goal for the field as stated in the decadal survey report is "to develop a comprehensive understanding of the formation, evolution, and destiny of the universe and its constituent galaxies, stars, and planets—including the Milky Way, the Sun, and Earth" (p. 3). The report then proposed five areas that are ripe for significant progress in the next decade. With those major scientific goals as a foundation, the report recommended a set of prioritized initiatives for the next decade (see Table 1.1). The new recommended initiatives have two important aspects. First, they are extremely challenging. Second, space- and ground-based astronomy and astrophysics each have critical roles, with

TABLE 1.1 Prioritized Initiatives (Combined Ground and Space) and Estimated Federal Costs for the Decade 2000 to 2010[a,b]

Initiative	Ground/ Space	Cost[c] ($M)
Major Initiatives		
Next Generation Space Telescope[d]	Space	1,000
Giant Segmented Mirror Telescope[d]	Ground	350
Constellation-X Observatory	Space	800
Expanded Very Large Array[d]	Ground	140
Large-aperture Synoptic Survey Telescope	Ground	170
Terrestrial Planet Finder[e]	Space	200
Single Aperture Far Infrared Observatory[e]	Space	100
Subtotal for major initiatives		2,760
Moderate Initiatives		
Telescope System Instrumentation Program	Ground	50
Gamma-ray Large Area Space Telescope[d]	Space	300
Laser Interferometer Space Antenna[d]	Space	250
Advanced Solar Telescope[d]	Ground	60
Square Kilometer Array Technology Development	Ground	22
Solar Dynamics Observatory	Space	300
Combined Array for Research in Millimeter-wave Astronomy[d]	Ground	11
Energetic X-ray Imaging Survey Telescope	Space	150
Very Energetic Radiation Imaging Telescope Array System	Ground	35
Advanced Radio Interferometry between Space and Earth	Space	350
Frequency Agile Solar Radio telescope	Ground	26
South Pole Submillimeter-wave Telescope	Ground	50
Subtotal for moderate initiatives		1,604
Small Initiatives		
National Virtual Observatory	Ground & Space	60
Other small initiatives	Ground & Space	246
Subtotal for small initiatives		306
DECADE TOTAL		4,670

[a]Cost estimates for ground-based capital projects include technology development plus funds for operations, new instrumentation, and facility grants for 5 years.

[b]Cost estimates for space-based projects exclude technology development.

[c]Best available estimated costs to U.S. government agencies in millions of FY2000 dollars and rounded. Full costs are given for all initiatives except the Terrestrial Planet Finder and the Single Aperture Far Infrared Observatory.

[d]Cost estimate for this initiative assumes significant additional funding to be provided by international or private partner; see *Astronomy and Astrophysics in the New Millennium: Panel Reports* (2001) for details.

[e]These missions could start at the turn of the decade. The committee attributes $200 million of the $1,700 million total estimated cost of the Terrestrial Planet Finder to the current decade and $100 million of the $600 million total estimated cost of the Single Aperture Far Infrared Observatory to the current decade.

SOURCE: Adapted from Table 1.2 in *Astronomy and Astrophysics in the New Millennium* (National Academy Press, Washington, D.C., 2001), p. 37. See that report for details on cost estimates, other small initiatives, and separate ground- and space-based priority lists.

high-priority projects in both arenas in roughly equal numbers. For example, the science goal of determining the large-scale properties of the universe is addressed by a combination of the Next Generation Space Telescope (NGST; a successor to the Hubble Space Telescope), the Giant Segmented Mirror Telescope (GSMT; a major advance in ground-based telescopes), and the Large-aperture Synoptic Survey Telescope (LSST; a ground-based survey telescope). All three future facilities are needed to address this science goal because NGST will image the most distant objects in the visible universe, GSMT will characterize the physical properties of these objects, and LSST will study the nature of the dark matter and dark energy that pervade the universe. NASA plays the crucial role in realizing NGST at a federal cost of nearly $1 billion. As conceived, GSMT and LSST would represent the most ambitious efforts ever undertaken in the NSF astronomy program, with a combined federal cost of more than $500 million out of total project costs of nearly $1 billion. NGST is already an international effort, and the two ground-based projects will almost certainly be multinational projects with significant contributions from the private sector.

The policy section of the decadal survey report concluded, in addressing organization and management issues raised by the Congress, that the astronomy and astrophysics research enterprise is currently robust and generally healthy. But the report goes on to express concerns similar to those found in *Federal Funding of Astronomical Research*, namely, that the balance among various components of the program (especially between the NSF and NASA grants programs) remains a concern, and that a large portion of the total support for astronomy is now tied to a few NASA flagship missions.

To address the question of balance, the decadal survey report recommended several steps to strengthen the ground-based program, including the following:

- National and independent observatories should be viewed as integrated systems of capabilities for the United States as a whole.
- Funds for grants for data analysis and the development of associated theory should be included in the budgets of major new ground-based facilities for their first 5 years of operation.
- The NSF should take more initiative in sharing with the general public the results of the scientific investigations NSF supports.

The decadal survey report further encouraged cooperation among NASA, NSF, and, for some projects, DOE. It recommended that these agencies work together with the research community to build new interagency programs and observed that the Office of Science and Technology Policy is the traditional broker for such cooperation.

The survey report also pointed out that, at NSF, provision of funds for research and analysis to capitalize on the observations made possible by new facilities is often neglected. Moreover, the NSF astronomy grants program is under heavy pressure to fund the analysis of the data obtained at these national ground-based facilities and the private/state observatories. This disconnect between facilities and the funds necessary to operate them differs from the results of NASA's policy of explicitly tying research funding to the successful peer-reviewed proposals for observations from a space mission. The report recommended that NSF include funding for operations, new instrumentation, and data analysis and theory grants for the first 5 years of operation when budgeting for each new large ground-based facility (see footnote (a) to Table 1.1).

2
Current Roles and Relationships of NASA and NSF in Astronomy and Astrophysics

The two primary funding agencies in astronomy and astrophysics, NSF and NASA, have different cultures and characteristics that derive from their different missions. The key aspects of the two agencies' mandates, organizational structures, program management approaches, and planning processes affect how they interact with each other and the implementation of the decadal survey recommendations. These characteristics provide the primary context for the committee's findings and recommendations, which are aimed at enhancing the positive synergy in astronomy and astrophysics research as described at the beginning of Chapter 1.

NASA

The NASA Act of 1958 (as amended) gives NASA responsibility for the aeronautical and space activities of the United States. It states a number of objectives, the first of which is "the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space." It authorized NASA to "arrange for participation by the scientific community," "acquire, construct, . . . operate and maintain laboratories, research and testing sites and facilities," "cooperate with other public and private agencies . . . in the use of . . . facilities," and "appoint such advisory committees as may be appropriate."

The NASA year 2000 strategic plan addresses advancing space science, the exploration of space, and space technology. There are five enterprises within NASA to carry out this strategy. One is the Office of Space

Science.[1] The Office of Space Science's charter includes developing and mounting space missions to study the universe, and promoting science education for the general public and for [K-12] students in particular. In the most recent internal reorganization of the Office of Space Science, an Astronomy and Physics Division was created.

Space missions are the primary vehicle through which the Office of Space Science achieves its scientific and educational objectives. NASA operates a number of laboratories and centers, which manage the implementation of most missions and support their operation. It provides grants to enable research based on the data generated by the missions. The research is carried out both in NASA centers and by investigators in universities and other laboratories. Mission planning is comprehensive and encompasses technology development, conceptual design, instrument development, launch, subsequent operations, data collection and distribution, and research and analysis. NASA supports a number of national centers to archive and distribute data generated by missions. The agency uses a structured and transparent project management process that employs full-time project managers, regular milestone reviews, and budgeting of contingency reserves. While the committee observed that NASA gets good marks in general for its project management expertise, some projects have encountered difficulties. Typically, when cost growth has occurred during the development of a scientific mission, the mission specifications, including science goals, have been modified to keep the expected overall cost below a specified ceiling.

The Office of Space Science maintains the federally chartered Space Science Advisory Committee under the auspices of the NASA Advisory Council. This committee gathers input from the external scientific community on mission priorities, strategic planning, and ongoing activities. It has subcommittees corresponding to the science theme areas defined by the Office of Space Science's strategic plan, as well as subcommittees for crosscutting areas such as technology development. Researchers selected broadly from the scientific community constitute the membership of the various committees. The chair of the Space Science Advisory Committee sits ex officio on the NASA Advisory Council. The Office of Space Science strategic planning process feeds into NASA's agency-wide planning process. The Space Science Advisory Committee takes into account the National Research Council's decadal reviews of astronomy and astrophysics and other reports and seeks NRC review of its strategy.

There is currently no formal mechanism for astronomy program coordination between NASA and NSF other than through the NRC's Com-

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[1]For more information see <http://spacescience.nasa.gov>.

mittee on Astronomy and Astrophysics (CAA). The CAA has strong scientific credentials but is not constituted to carry out technical program reviews or management critiques. NASA seeks advice from the CAA via its parent boards (the Space Studies Board and the Board on Physics and Astronomy) on occasional mission-related questions, such as whether the overall scientific goals can still be achieved when a mission is descoped. The committee notes that the agencies have never jointly asked for formal advice of any kind from the CAA, even though the decadal surveys are jointly commissioned.

NSF

The NSF Act of 1950 established NSF "to promote the progress of science; to advance the National health, prosperity, and welfare; (and) to secure the National defense." It directed NSF to support "basic scientific research and research fundamental to the engineering process . . . ." NSF also has a charter to strengthen science education.

The NSF is dedicated broadly to the advancement of science and engineering through support of university-based research. NSF undertakes a responsibility to support education and training at all levels and has a primary responsibility for the long-term continuity of the research effort and the maintenance of the scientific workforce on a generational time scale.

The NSF is governed at the top level by the National Science Board. The management of the program is divided into directorates and several cross-cutting divisions and offices. The Astronomical Sciences Division in the Mathematical and Physical Sciences Directorate has primary federal responsibility for ground-based astronomy and astrophysics research, including optical/infrared, solar, and radio astronomy. NSF also supports a small amount of research in ground-based planetary astronomy. It is important to note that significant sources of research support for astronomy and astrophysics research are spread broadly across NSF. The Office of Polar Programs supports several astrophysical experiments in Antarctica. Solar research at NSF is supported by both the Astronomical Sciences Division and the Division of Atmospheric Sciences in the Geosciences Directorate. The Physics Division is also a significant source of support for astrophysics research. (See Appendix C for more details.)

Radio astronomy is an almost entirely ground-based effort, so NSF is by far the primary source of funding in this subfield. While NSF's general approach to large projects is to respond to proposals from the university community and to not impose a vision on that community, it has consistently supported, at the initiative of the National Radio Astronomy Observatory, the Observatory's design and development efforts for the

Atacama Large Millimeter Array. The NSF is also the primary source of support for the Arecibo Observatory (a 300-meter single-dish radio telescope) through the National Astronomy and Ionosphere Center.

The NSF supports three major national optical/infrared observatories: the National Optical Astronomy Observatory, which is responsible for a suite of moderate and small telescopes in the northern and southern hemispheres that are widely available to the astronomy and astrophysics community; the Gemini Observatory, two 8-meter telescopes (northern and southern hemisphere) with the United States supporting roughly half of the international collaboration; and the National Solar Observatory, which operates solar telescopes widely available to the community.

The Astronomical Sciences Division's strategy is to seek answers to a number of science questions covering the major issues in the field and to explore cross-disciplinary connections with related fields such as physics. Implementation focuses on strengthening the discipline via the grants program, development of new instruments and technologies, and operation of national observatories. Improving education as well as public understanding of science and NSF's role in new discoveries also figures in the strategy.

The grants program at NSF is administered by individual discipline scientists and it funds the best ideas generated by the university-based research community, as judged by competitive peer review. Research grants are funded separately and independently from facility construction and operations. Project development and operations are conducted by outside entities—usually academic consortia or individual universities. The typical user who has been awarded observing time on a telescope through a competitive peer review process may also apply to NSF for a grant to carry out the research.

A remarkable circumstance exists in the area of nighttime ground-based optical/infrared telescopes: Most of the U.S. facilities of this kind are built by universities with private and state funds. Developing a viable policy for providing public funds for adequate instrumentation of non-federal ground-based optical telescopes is a challenge that remains to be met. The NSF is establishing a new telescope instrumentation program to provide such funds since the inadequacy of the instrumentation for independently funded telescopes limits scientific exploitation of this great scientific asset. (The history of the instrumentation program is discussed in greater detail below in the section "Issues Affecting NASA and NSF Implementation of Decadal Survey Priorities.")

In keeping with the prominence of education in its charter, NSF and its Astronomical Sciences Division strive to support researchers in small colleges and universities, which are a source of much of the scientific workforce. NSF operates a successful agency-wide program—Research in Undergraduate Institutions—that provides support for such researchers. In addition, it conducts the popular Research Experiences for Undergraduates program. The Astronomical Sciences Division reflects the long-term NSF concern for education of the next generation of researchers at all levels and participates strongly in the Research in Undergraduate Institutions and Research Experiences for Undergraduates programs. Astronomy lends itself particularly well to attracting new cadres of students into science because of the fascination that the subject matter holds for inquiring young minds.

The Mathematical and Physical Sciences Directorate has a federally chartered advisory committee that provides advice on program direction. Like the advisory committees for other directorates, it is not formally linked with the National Science Board, by statute the highest authority in NSF. In response to a federal directive in the early 1990s NSF abolished its division-level advisory committees, so the Astronomical Sciences Division does not now have a dedicated advisory committee to assist in strategic planning. Astronomical Sciences Division staff prepared a strategy document in 1998-1999 that was then refined with assistance from a small ad hoc group of astronomers. Community input to the Astronomical Sciences Division regarding scientific direction comes from the Mathematical and Physical Sciences Directorate advisory committee and the NRC's Committee on Astronomy and Astrophysics. The Committee on Astronomy and Astrophysics can provide, as described above, a forum for NASA-NSF coordination at a strategic policy level, although the NRC's rigorous and lengthy review and approval process limits rapid responses for more immediate tactical advice. Like other divisions, the Astronomical Sciences Division does have a visiting committee that reviews its activities every 3 years, but the reviewers are encouraged to concentrate on verifying that the granting process is being carried out correctly rather than addressing strategic planning.

The Division of Physics at NSF has developed a unique and effective scheme for obtaining advice on high-energy and nuclear physics by partnering with the Department of Energy (DOE) in the operation of the federally chartered High Energy Physics Advisory Panel and the Nuclear Science Advisory Committee. Each advisory committee provides a forum for DOE-NSF joint strategic planning in these disciplines. The agencies also operate a non-advisory body called the Science Assessment Group for Experiments in Non-Accelerator Physics that provides a mechanism for scientific assessment of project proposals in particle astrophysics and other non-accelerator-based physics of mutual interest to NSF and DOE. These panels can serve as a model for providing external expert advice to federal agencies and for interagency cooperation and coordination. (See Box 2.1 for more details.)

BOX 2.1 NSF-DOE Joint Advisory Panels: One Model for Coordination

The National Science Foundation (NSF) and the U.S. Department of Energy (DOE) have created two advisory committees to help them coordinate and direct research in fields where both agencies have an interest. These committees could serve as a model for a similar NSF-NASA external group that would advise the agencies on their astronomy research programs.

The Nuclear Science Advisory Committee (NSAC), founded in 1977, serves to "advise DOE and the NSF on scientific priorities within the field of basic nuclear science research."[1] This mandate covers both experimental and theoretical investigations into the structure and properties of atomic nuclei, as well as their fundamental interactions. Recently, NSAC has been asked to develop a new long-range plan for nuclear physics research in the United States. The committee is tasked by the agencies to identify resource requirements in terms of both people and facilities, and to recommend appropriate funding levels. A similar plan produced by NSAC in 1996 was instrumental in the construction and upgrade of many facilities, including the Thomas Jefferson National Accelerator Facility's Continuous Electron Beam Accelerator Facility, the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory, and the National Superconducting Cyclotron Laboratory at Michigan State University.

The NSF and DOE also support a committee that reviews the nation's high-energy physics research programs. The High Energy Physics Advisory Panel (HEPAP) has a mandate very similar to that of NSAC, in this case giving advice on research priorities, funding levels and balance, and potential changes based on new discoveries or technology in the realm of high-energy physics. HEPAP was created in 1967 to advise the DOE, and NSF formally joined on January 1, 2001. High-level administration support—through the Office of Science and Technology Policy—for the HEPAP-backed plan for U.S. participation in the European Large Hadron Collider has been credited with making that arrangement succeed. HEPAP is currently engaged in a significant long-range planning process for high-energy physics.

The advisory groups are both standing panels, composed of approximately 20 members, that meet three times a year to review the programs. The national laboratories, laboratory user groups, and the American Physical Society's Division of Particles and Fields suggest potential HEPAP members, who are drawn primarily from academia, as well as from the various national laboratories. NSAC members are chosen in a similar manner. The two groups engage in long-term planning, a task generally undertaken by ad hoc subcommittees of the advisory committees.

The DOE and NSF also operate the Science Assessment Group for Experiments in Non-Accelerator Physics (SAGENAP). SAGENAP was assembled in 1996 to facilitate cross-agency decision making on project proposals in particle astrophysics. This body enables the accelerator community to have a voice in government funding of non-accelerator physics experiments. At its own request, NASA has observer status in SAGENAP.

NSAC and HEPAP are both chartered under the Federal Advisory Committee Act, but SAGENAP is not.

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[1]The NSAC charter is available online at <http://www.er.doe.gov/production/henp/np/nsac/charter.html>.

COORDINATION BETWEEN NASA AND NSF

In the past, when presented with the list of project priorities in the decadal surveys, NASA and NSF have taken their respective halves of the separated ground/space list and have realized those projects to the best of their abilities. This approach has been quite successful thus far, as demonstrated by the current well-being of the field; however, it is not clear that this independent approach will continue to be as effective as facilities continue to become more interdependent and costly into the future. Operating now according to separate agendas, NASA and NSF often fail to coordinate, cooperate, or even communicate with each other. There are exceptions, of course, on the level of interactions between individual program officers and discipline scientists, but even these are rare. The committee was surprised to learn, for example, that the current head of NASA's Office of Space Science and the current head of NSF's Mathematical and Physical Sciences Directorate have never met with each other to discuss their respective program plans. The committee believes that interagency communication, coordination, and cooperation are critical to the future of an effective national astronomy and astrophysics enterprise, and so it was encouraged to learn that interactions between relevant NASA and NSF managers have recently increased. To ensure interagency coordination, the committee believes that the Executive Office of the President should be involved.

The Office of Science and Technology Policy (OSTP), backed by the budgetary authority of the Office of Management and Budget (OMB), has had experience in coordinating complex programs in the federal government by creating multiagency committees. Both White House offices have specific charges to oversee, and in OSTP's case lead, efforts to ensure interagency cooperation. For example, OSTP's enabling legislation includes charges for the office to "lead an interagency effort to develop and implement sound science and technology policies and budgets" and to "build strong partnerships among Federal, State, and local governments, other countries, and the scientific community."[2] Similarly, a key role of OMB is "to help improve administrative management, to develop better performance measures and coordinating mechanisms."[3] Both offices have played these roles in other interagency forums. (See Box 2.2.)

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[2]National Science and Technology Policy, Organization, and Priorities Act of 1976, Public Law 94-282. See the OSTP Web site at <http://www.ostp.gov> for more details.

[3]See OMB's Web site at <http://www.whitehouse.gov/omb> for more details.

BOX 2.2 White House Coordinated Interagency Programs

National Oceanographic Partnership Program (NOPP)

The NOPP was created in response to PL 104-201, the National Defense Authorization Act of 1997, to facilitate multiagency support of oceanographic research and education. The National Oceanographic Research Leadership Council (NORLC) oversees the program. It is composed of the heads of the 12 participating agencies, including the Office of Management and Budget (OMB) and the Office of Science and Technology Policy (OSTP), and is chaired by the Secretary of the Navy. An Interagency Working Group comprising senior staff members from all participating agencies performs staffing functions assigned to it by the NORLC, and an Ocean Research Advisory Panel composed of senior scientists drawn from non-profit organizations and industry provides independent outside advice to the NORLC.

Federal Information Technology R&D Program (formerly the High Performance Computing and Communications Initiative)

Coordination of federal information technology research and development is the responsibility of the Interagency Working Group on Information Technology R&D (IWG/IT R&D). The IWG has representatives from 12 participating agencies, and it reports to OSTP through the National Science and Technology Council (NSTC). The IWG coordinates planning, budgeting (including preparation of annual crosscut budgets), and assessment activities in an area where a number of agencies play important roles but where no one agency claims IT R&D as its primary mission.

United States Global Change Research Program (USGCRP)

Overall direction and executive oversight of the USGCRP have been the responsibility of the Subcommittee on Global Change Research, which reports to OSTP and OMB through the NSTC. The subcommittee includes representatives from 14 participating federal agencies, plus OMB and OSTP, and its major duties have included the preparation of annual crosscut budgets. Assessments of the effectiveness of this process have been mixed (see Space Studies Board, National Research Council, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design*, National Academy Press, Washington, D.C., 2000, p. 14).

ISSUES AFFECTING NASA AND NSF IMPLEMENTATION OF DECADAL SURVEY PRIORITIES

NASA—with important international contributions from, for example, Europe, Japan, and Canada—has been quite successful in implementing the large space initiatives recommended in the decadal surveys. Nearly all of the missions recommended in the current decadal survey report have been incorporated into NASA's strategic plan. Large space missions recommended in past and current decadal surveys (e.g., the Chandra X-ray Observatory, the Space Infrared Telescope Facility, and the Next Generation Space Telescope) almost always experience significant cost growth as a result of formidable technical challenges and other issues. As mentioned earlier, when such cost growth occurs, NASA typically reduces the mission's capabilities to maintain the project's cost and technical feasibility. If a so-called "rescope" or "descope" of the mission becomes necessary, NASA consults with its internal advisory panels in an attempt to minimize the scientific losses of the revised mission concept and asks the NRC to review and assess the scientific validity of the new mission in light of the original decadal survey recommendation for the mission. The agency also makes difficult, and in many cases controversial, decisions in considering the trade-offs between developing new astronomy and astrophysics missions and devoting those resources to supporting the operations and research programs of older missions that are still producing interesting scientific results. One of the most important examples of such a trade-off is evident in the case of the Hubble Space Telescope and the Next Generation Space Telescope. Both missions share the same funding line in NASA's Office of Space Science budget, so funds for the design, development, construction, and eventual operation of the Next Generation Space Telescope must be balanced against the costs of upgrades, operations, and research support for the Hubble.

In the Gemini project, NSF has successfully responded to two of the three major ground-based recommendations of the 1990s decadal survey.[4] Currently, NSF is moving forward with the implementation of the remaining major initiative of the 1990s decadal survey, the Atacama Large Millimeter Array. NSF does not yet have a viable strategy to implement the major ground-based facility initiatives of the current survey within current budget estimates. Assignment to the Major Research Equipment budget line is NSF's main mechanism for funding large facility initiatives. Increased competition for Major Research Equipment funding, combined with an increase in the scope and cost of ground-based astronomy facilities and instrumentation, will make it difficult for NSF to formulate and implement the needed strategy.

Even if funds were made available to implement all of the initiatives recommended in the current decadal survey, the issue of NSF's large project management remains. Several staff members in the Executive

[4]The Gemini Observatory includes both the northern and southern hemisphere telescopes recommended in *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington, D.C., 1991).

Branch and in Congress conveyed to the committee their perception that NSF does not manage large projects well and their frustration with the general lack of openness and transparency in NSF's internal priority setting and management of the large projects funded through NSF's Major Research Equipment account. Concerns about NSF's ability to construct and operate the large ground-based projects proposed in the current decadal survey were formally expressed in the 2002 budget document that requested the present study,[5] and NSF was directed to produce a plan to enhance its capabilities for managing large projects. The committee heard testimony on the issue of large project management at NSF and discussed it with several high-level project managers with significant experience in large federal construction projects. At its second meeting, the committee was also provided with a brief summary of an interim report on NSF project management. NSF is scheduled to deliver its final report to the Office of Management and Budget and to Congress in September 2001.

In addition, NSF's astronomy program has large ongoing commitments to various existing ground-based astronomy institutions. Thus, the fraction of the Astronomical Sciences Division's budget available for unsolicited grants to university investigators is relatively small. Addressing this imbalance was recommended as the top priority overall by the 1990s decadal survey, but it has not been possible for the Astronomical Sciences Division to do so within present budget constraints.

Ground-based optical astronomy is unique in that most of the major facilities in this field in the United States are university-based telescopes whose construction is independently funded. This group of facilities could be thought of collectively as a third major player in ground-based optical/infrared astronomy, along with NASA and NSF. This third group has brought enormous resources into the field. The council of directors of these facilities (the AURA Coordinating Council of Observatory Research Directors, ACCORD) strives to coordinate the facilities' policies, but it does not have the power of governance. Consequently, this major component of U.S. astronomy is fractured and has not dealt with its principal problem: funding the instrumentation that is necessary to fully exploit the scientific potential of its telescopes.

In 1995, an ad hoc panel[6] of the Committee on Astronomy and Astrophysics recommended that NSF assume responsibility for providing the

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[5]Executive Office of the President, *A Blueprint for New Beginnings: A Responsible Budget for America's Priorities*, U.S. Government Printing Office, Washington, D.C., 2001.

[6]The National Research Council panel, chaired by Richard McCray, authored the report *A Strategy for Ground-Based Optical and Infrared Astronomy* (National Academy Press, Washington, D.C., 1995).

instrumentation needed at the independent telescopes. It also recommended that the independent observatories offer observing time to individuals not affiliated with the sponsoring universities in return for this funding. The plan was referred to as the Facilities Instrumentation Program.[7] Although the original instrumentation plan was not considered to be a success because of the limited participation by the private and state observatories, the most recent survey committee and its optical/infrared panel[8] strongly endorsed the fundamental tenets of this instrumentation program as a way of increasing the overall research infrastructure for the discipline. As a result, the survey committee modified the plan so that it would be more appealing to the private and state observatories and renamed it the Telescope System Instrumentation Program.[9] It was the express hope of these previous NRC's panels that if NSF could offer a large enough incentive, it could simultaneously increase the discipline's research infrastructure through instrumentation at the private/state observatories and exert leadership in ground-based optical/IR astronomy.

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[7]The Facilities Instrumentation Plan was endorsed again, though slightly revised, by the Committee on Astronomy and Astrophysics in a letter report issued in response to a request by ACCORD and NSF's Astronomical Sciences Division to consider an alternative plan proposed by ACCORD ("Letter Report on the Revised Facilities Instrumentation Program of the National Science Foundation," Board on Physics and Astronomy and Space Studies Board, National Research Council, Washington, D.C., June 2, 1999).

[8]The report of the Panel on Optical and Infrared Astronomy from the Ground is included in *Astronomy and Astrophysics in the New Millennium: Panel Reports* (National Academy Press, Washington, D.C., 2001).

[9]The Telescope System Instrumentation Plan was the top-ranked moderate initiative in the most recent decadal survey report.

3
Advantages and Disadvantages of Moving NSF's Astronomy and Astrophysics Responsibilities to NASA

There are advantages and disadvantages to moving NSF's astronomy and astrophysics responsibilities to NASA. Since each agency's role in astronomy and astrophysics must be viewed in the context of its broader charter and its culture, it is useful to summarize the salient features of the two agencies before discussing the consequences of a transfer.

NASA's charter focuses on space science. NASA launches space missions and conducts related research. It has a highly organized system (using independent advisory committees) for strategic planning of these missions and their operation, and it carries out its work through internal facilities, centers, and laboratories supported by extramural research funds. The management style has a significant "top-down" nature. NASA is a larger agency than NSF and, although its grants program is primarily mission-related, it now funds most of the work of the astronomy and astrophysics community.

NSF's charter is to fund a broad range of science, develop and maintain the U.S. research infrastructure (both people and facilities), and promote education. NSF responds to proposals from the university science community and works through universities or consortia of universities. NSF is also responsible for a number of ground-based observatories and has begun to plan in terms of science-theme initiatives, an effort that itself requires strategic planning. Nevertheless, NSF still strives to remain flexible to enable it to respond to changing directions in research as proposed by individual investigators. This broader orientation, in contrast to NASA's emphasis, reflects a more "bottom-up" approach to management.

There are several fundamental issues to be addressed when considering the advantages and disadvantages of the transfer of NSF's astronomy and astrophysics responsibilities to NASA:

- Integration of ground- and space-based research

It is certainly plausible that a well-integrated program would emerge if all astronomy and astrophysics operations were the responsibility of a single agency. Integration of the space and ground parts of astronomy and astrophysics research was a high priority of the most recent decadal survey report. Bringing the federally funded astronomy and astrophysics effort into one agency could facilitate this integration.

- Integration of privately and federally funded ground-based optical/infrared programs

For ground-based optical/infrared astronomy, much of the observing power resides in telescopes constructed with private and/or state funds and owned and operated by universities or private institutions. Incorporating the NSF astronomy and astrophysics program into the NASA organization would not, by itself, solve a major issue in ground-based astronomy, namely, effective integration of the private telescope facilities into the larger system. Since working closely with the university community is a traditional NSF strength, that agency seems better suited to address this problem.

- Efficiency of program and project management

While both agencies have from time to time encountered serious problems in managing specific projects, each has had overall success in project management. On one hand, moving ground-based astronomy into NASA would enable the application of its disciplined style of project management, with announcements of opportunity and integration of technology development, conceptual design, instrument development, operations, data collection and distribution, and research and analysis. On the other hand, NSF could achieve the same objective without disrupting its active astronomy program by strengthening its style of project management. Establishing practices that allow for stable long-term operation and optimum scientific use of facilities would have many advantages for NSF and its growth strategy. Open bidding for all phases of new national facilities would directly strengthen the university research community, and thereby the field. In addition, NSF has the flexibility to respond to new ideas and proposals that emerge from that community in areas not anticipated by "top-down" strategic plans and not associated with major facilities, missions, or science themes. The separation of this grants program from new initiative funding in NSF protects the program from fluctuations created by the changing needs of many projects. The committee notes that the operations of both agencies are already streamlined to the point that there is little possibility for economies of scale in transferring NSF's astronomy and astrophysics operations to NASA.

- Budget constraints on very large ground-based projects

The top-ranked large ground-based initiative recommended by the decadal survey report is the Giant Segmented Mirror Telescope. Unless the NSF Astronomical Sciences Division budget enjoys extraordinary growth over the next decade, the Giant Segmented Mirror Telescope will be too costly to be pursued. The scale of the Giant Segmented Mirror Telescope is more commensurate with NASA missions; however, either agency would require a concomitant budget enhancement to enable construction of this telescope. NSF's Major Research Equipment account, or something like it, could be expanded to accommodate more initiatives, enabling NSF to respond to the most recent decadal survey report's recommendations. This action might also assist NSF's growth strategy. At the present time, the Office of Space Science's interpretation of NASA's charter (which does not explicitly prohibit sponsoring ground-based research) makes it unlikely that NASA would accord high priority to ground-based initiatives such as the Giant Segmented Mirror Telescope.

- Production of a scientific workforce for the future

NASA concentrates primarily on missions and to a considerable degree presupposes the existence of a cadre of researchers, although it has been active in promoting K-12 education. NSF has as an explicit top-level goal the development of the nation's university research capability and the proactive development of a scientific workforce for the future. NSF is a resource for funding research-based education within the small colleges that produce a substantial fraction of scientists in the United States. There is no comparable activity of this scope in NASA and no obvious niche for it. NSF also has accepted a responsibility for helping to ensure the long-term continuity of university research groups, for example by funding a wide range of instrumentation for ground-based astronomy. The students trained in these programs are the "seed corn" for all types of future instrumentalists, and the university research groups constitute the intellectual infrastructure on which the continuing training capacity rests. NASA has a more specialized role in supporting space instrumentation (much of it developed at national laboratories). The transfer of astronomy and astrophysics at NSF to NASA could result in erosion of this training resource due to the time and budget pressures of NASA's core space mission.

- Public information and outreach programs

Public awareness of astronomy and astrophysics has been enhanced by NASA's public education and outreach effort, which has been highly successful. NASA's admirable lead in this arena could be followed for ground-based astronomy. NSF could adopt some of NASA's more successful strategies aimed at informing the press and the public about the research that it funds. Efforts in this direction are now in progress at NSF, although top-level support backed by substantial funding for these efforts will be necessary.

- Diversity of funding opportunities

NASA missions have a finite lifetime, and continuity depends on dovetailing their funding envelopes as time and fiscal pressures dictate. Any major space science mission failure could have a considerable impact on the NASA astronomy and astrophysics program and its community. Overruns in major programs such as the space station have the potential to negatively affect the space astronomy and astrophysics program, although the current NASA administration has not so far allowed the problems with the space station to affect the space science enterprise. In contrast, NSF, by design, fosters continuity in the intellectual development of the community. It also provides members of the research community with an alternative funding avenue for programs that NASA might find difficult to fund for programmatic reasons. This diversity is healthy for the field. The loss of NSF as an independent actor in astronomy and astrophysics would deprive the field of an important source of stability, continuity, and diversity. In fact, the vulnerability of the discipline to the catastrophic loss of a major NASA mission argues for a greater rather than a lesser role for NSF.

- Stewardship of ground-based astronomy

NASA operates missions and laboratories and conducts some of its own research. NSF has a charter to support the public ground-based observatories and university-based research, including instrumentation and some share of the operation of private telescope facilities. Its responsibilities encompass not only optical/infrared but also radio instruments. NASA has little experience in radio astronomy. By contrast, NSF has been sufficiently successful in supporting radio astronomy facilities to now be mounting a major international initiative (the Atacama Large

Millimemeter Array), and a transfer might disrupt the progress of this effort given NASA's lack of expertise.

- Interdisciplinary connections

NSF is primarily a science agency. NASA is primarily a mission agency. Increasingly, the frontiers of science are multidisciplinary, and NSF is chartered to act as a general science agency, linking various disciplines together where appropriate. The loss of such potential linkages would be harmful to the development of astronomy and astrophysics. Basic research across the sciences, but especially astronomy and astrophysics, would be adversely affected by loss of the role that NSF plays in enabling interdisciplinary research between the astronomical and astrophysical sciences and, for example, physics (particle, gravitational, nuclear, atomic, molecular and optical, plasma, and condensed matter), computation, mathematics, chemistry, and geophysics. Although NASA has a role in the interagency information technology initiative that is creating the powerful grid-based supercomputing capability needed by all of science and engineering, the main players are NSF and the Department of Energy, and to a lesser extent, the Department of Defense. The probable loss of synergy across all of the aforementioned fields is a prime argument against an administrative move of the NSF astronomy program to NASA.

In conclusion, the committee finds that the potential advantages of transferring NSF's astronomy and astrophysics responsibilities to NASA are outweighed by the advantages inherent in retaining a leadership role for NSF in ground-based astronomy and astrophysics.

4

Findings and Recommendations

Although the strong recommendation of the committee is against transfer of NSF's astronomy and astrophysics responsibilities to NASA, the committee did find clear evidence for legitimate issues and potentially troublesome trends that require attention. The scientific challenges in astronomy and astrophysics are very broad and fall within the scope of several agencies. Responding to each challenge will require a coordinated approach combining the strengths and resources of all three major astrophysics-related agencies—NSF, NASA, and DOE—as well as other participants.

The recent profound changes in the field of astronomy and astrophysics cited in Chapter 1 of this report and in the findings below raise questions as to whether the management structures that were in place throughout the latter part of the 20th century are still appropriate for the first part of the 21st century. The primary concerns of the committee and prior studies are summarized in Box 4.1. Focusing on the roles of NSF and NASA, the committee endorses an integrated approach to addressing many of these high-level concerns affecting the future health of astronomy and astrophysics research in the United States. The committee also recognizes that there are more specific, complex, and long-standing issues within the discipline—especially in the ground-based optical/infrared community—and that these specific issues have been thoroughly addressed by previous panels in much greater detail. The approach presented below in the form of seven findings and six recommendations attempts to create a new overarching framework to address most of the

BOX 4.1 Summary of Concerns That Require Attention

- The inadequate coordination between NASA and NSF that results in lack of coherent planning for the federally funded portion of astronomy and astrophysics. This lack of coordination has the potential to reduce opportunities and increase inefficiencies and is detrimental to both space missions and ground-based pursuits.
- The impact of insufficient coordination of the federal program in astronomy and astrophysics with the activities supported at state, local, and private levels, particularly given the substantial investment of the latter institutions in ground-based optical/infrared astronomy. This fragmentation is a long-standing problem but also represents an opportunity to strengthen the overall astronomy and astrophysics research enterprise in the United States.
- The lack of a clear mechanism for coordinating, in an integrated fashion, the activities of the United States in ground-based astronomy and astrophysics with those of other nations.
- The practice at NSF of making major investments in facilities without providing adequate funds to (1) ensure the availability of instruments for optimal exploitation of the facilities and to (2) underwrite the necessary supporting research grants to enable theoretical work and the analysis and publication of the data.
- The perceived imbalance between support for space-based and ground-based astronomy (with the latter generally considered to be inadequate).
- The perceived management shortcomings of NSF in conducting major projects.
- The growing vulnerability of the astronomy and astrophysics research talent base to disruption caused by the failure of a major space mission (such as the Hubble Space Telescope).

high-level concerns. This new framework should facilitate the resolution of specific, but important, lower-level issues as well.

FINDINGS[1]

Established Effectiveness of the Federal Organization

The best measure of the overall effectiveness of the federal organization for astronomy and astrophysics is the results of research supported by it. The accomplishments in this field, particularly in the last decade, speak for themselves. Observations have given rise to deep theoretical insights about planets, stars (including the Sun), galaxies, and the history

[1]The committee's findings are generally consistent with the policy conclusions of the most recent decadal survey committee.

of the universe. Recent observations of the Sun have helped scientists understand better how it interacts with Earth and have revealed much of its inner workings (forcing particle physicists to confront and test the fundamental nature of neutrinos). Cosmology has becomes a quantitative science yielding profound insights about the origin and fate of the universe. The Hubble Space Telescope has enabled study of the universe at greater distances and farther back in time than ever before, in the process revealing evidence for the acceleration of the expansion of the universe. Evidence has grown that most galaxies have at their cores enormous black holes. This list could go on for many pages. NASA and NSF support of the astronomy and astrophysics community, of key missions and instruments, and of various planning processes, including the decadal surveys, has been crucial to most of this work. The committee concluded that the federal system has performed its function in support of astronomy and astrophysics research very well over the last decade. But it is clear that the field now faces a new level of challenges. Continued success depends on making some adjustments to the current system to realize the ambitious priorities for the future that have been set forth in the most recent decadal survey report. An integrated national program that fully exploits the synergies of ground- and space-based observations over all wavelengths and using new probes such as gravity waves and neutrinos is needed to address the challenges of the new millennium.

Implications of the Interdependence of Space- and Ground-based Astronomy

Innovative facilities require an integrated system and new approaches to coordination. The new astronomical facilities proposed in the recent decadal survey report are much more powerful and unavoidably more expensive than those currently available. Their construction and operation will be beyond the means of private donors and perhaps even those of single agencies or nations. For all these reasons, enhanced levels of collaboration among institutions, government agencies, and nations are now required.

Consequential Changes in Opportunities for Federal Agencies

Even as NASA becomes more dependent on ground-based science, it is likely to remain a space-mission-focused agency, working mainly through its own national centers, with emphasis in the areas of astronomy most related to space observations. Nevertheless, scientific outcomes now depend on integrated space- and ground-based observations in addition to new instrumentation, theory, supercomputers, and increasingly sophisticated data storage and analysis. NASA needs to make use of all pertinent tools, including ground-based observatories, if it is to maximize the outcomes of its suite of space missions.

The NSF pursues science in the broadest sense and encourages connections between astronomy and physics, geophysics, computation, mathematics, chemistry, and other disciplines. It is responsible for ensuring the depth and breadth of the U.S. academic research capability and has a specific charge to foster the education of young scientists on which that capability ultimately rests. Although in the past NSF has been responsible for the successful design and construction of large astronomical facilities, its administrative and financial resources have frequently been insufficient to ensure optimal operation and maintenance of these facilities. For example, the organizational plans for ground-based astronomy and lines of responsibility for decision making at NSF and its facility contractors are frequently not as clear as they should be. This situation, if not ameliorated, will challenge NSF's ability to respond to the challenges posed in the most recent decadal survey. The slow growth of the NSF astronomy research budget over the last decade, coupled with the cost of new telescope facilities and the many competing demands within NSF, has exacerbated these issues.

Issues in Ground-based Optical/Infrared Astronomy and Astrophysics

By a substantial margin, NSF does not have the resources to keep U.S. ground-based optical and infrared astronomy at the world level. Fortunately two sources of funding have eased the situation in the last decade: non-federal investments from private and state government resources for the construction of new telescopes, and international sharing of costs for the largest optical project NSF has been able to accomplish (i.e., the Gemini Observatory). This dependence on private, state, and international resources is both a blessing and a burden. The blessing comes because these projects, which could not have been built by NSF alone, have allowed the United States to stay abreast of the state of the art. A burden arises domestically because it appears that a contribution to the costs of the operation and/or instrumentation of the private observatories by NSF is a key to optimizing the scientific return from these facilities and to providing access to them for the broader U.S. community. A burden arises internationally because the international cost-shared projects are still very expensive and require a level of managerial complexity that has proved a challenge for NSF's Astronomical Sciences Division.

The substantial private and state investments in telescope facilities have resulted in the construction of a number of university-based, large telescope facilities, whose directors have joined together to form a common council known as ACCORD. The state and private resources alone are not sufficient to operate and instrument telescopes so as to optimize their potential. Yet, the private foundations and states that fund construction of these independent facilities want to see maximum impact from their investments. There is thus an opportunity to serve the broad community of U.S. astronomers by providing access to the private and state facilities in exchange for support by NASA and NSF to enhance the capabilities of these observatories. An important consequence of such an approach would be to foster coherent system-wide planning for funding the operation, maintenance, instrumentation, and research at the private and public telescopes. Because of NSF's strong involvement in ground-based astronomy through its funding of the national centers and the university community, it seems natural to assign the responsibility for organizing a coherent overarching plan to its Astronomical Sciences Division. NSF now has limited leverage with the ACCORD institutions and therefore did not play a central role in the decisions that have led to the current situation. Nevertheless, because of the tremendous potential that these facilities have to advance astronomy, the Astronomical Sciences Division has initiated the new Telescope System Instrumentation Program to address the need for instrumentation at the private telescopes. This program will provide grants for instrumentation with the provision that awardees make observing time (or a similar resource or product) available to the astronomy and astrophysics community at large and not just to their own staffs. It has proved difficult for the Astronomical Sciences Division to negotiate the detailed terms of agreement under past versions of this program, but it is currently discussing the parameters of this new program with the university community. Whether a government agency can leverage the large private and state investment—to the benefit of the entire field—by providing effective coordination of a group that includes independent entities remains to be seen, but the proposition cannot be tested unless NSF can provide sufficient incentives.

The one public institution funded by NSF that operates ground-based optical/infrared telescopes for general use by the astronomy community is the National Optical Astronomy Observatory. The National Optical Astronomy Observatory was assigned a leading role in the major ground-based optical/infrared initiatives recommended in the 1990s decadal survey report: the Gemini Observatory. These two telescopes are now the crown jewels of publicly funded ground-based optical/infrared astronomy. There has been heavy criticism from the astronomy and astrophysics community of the handling of the negotiations with international partners for the construction and operation of the Gemini Telescopes. The European partners were uncertain about the lines of authority in the

United States and, in response, NSF created a Gemini Observatory organization separate from the National Optical Astronomy Observatory. The astronomy and astrophysics community believes that this process has ultimately weakened the U.S. position in the project. It is arguable that allowing an open competition for the management of the Gemini project would have resulted in a stronger leadership organization taking control. It is undoubtedly true that the existence of a more systematic and transparent project management process within NSF would have enabled the Astronomical Sciences Division to take a stronger hand in dealing with the issues in this case.

With such a field of players spanning the private and public sectors, there is a need for clear lines of responsibility to be defined by the NSF when it awards contracts for facility construction and management in astronomy and astrophysics. Unless NSF reviews and approves revised mission statements and performance plans for each organization that is involved, responsibilities and lines of authority will remain loosely defined at best. Such a lack of clarity will place the United States at a disadvantage in negotiations with international partners. If NSF funds and promotes a strong program of support for instrumentation and research at the private observatories, it should be able to acquire enough leverage to foster system-wide coordination and planning.

Although private donors and states have built the bulk of the new, large optical observatories in the United States in the recent past, it is unlikely that they will be able to provide by themselves for the next generation of even larger telescopes. This is another reason for concluding that ground-based optical/infrared astronomy would benefit from being organized into an efficient, integrated system involving a close and effective partnership between the federal government and private and state observatories. A unifying national mechanism is also needed to ensure the cooperation of the universities and independent observatories in developing the next generation of telescopes.

Policy and Structural Issues in NASA and NSF

NASA's policy with respect to future investments in ground-based observations rests primarily on the relevance of these observations to planned space missions. As NASA increasingly commits to science-based criteria in measuring the success of its activities, it can maximize the scientific output and cost-effectiveness of its missions by recognizing the increased importance of utilizing the growing power and resolution of ground-based observatories for precursor and follow-up measurements.

The NSF has designed and constructed large astronomical facilities, it operates a fair and productive research grants program, and it fosters the development of young scientists. Nevertheless, the operation of NSF astronomical facilities would benefit if the lines of responsibility between NSF and its contractors were more clearly defined. NSF's strategic decision making could also be more transparent to its contractors, to Congress, and to the scientific community that it supports. Transparent decision making is particularly important for the successful development of an integrated program in astronomy and astrophysics. The current NSF advisory committee structure is not well suited to the developing opportunities in ground-based astronomy, which require extensive strategic planning. It is important to reestablish an external advisory structure for NSF's Astronomical Sciences Division in order to ensure that its strategic planning captures the breadth of vision of the whole community.

The committee did not find evidence that NSF has significantly more problems during the construction phase of large projects than do NASA, DOE, or other similar agencies. However, the committee found that the NSF lags other agencies in establishing transparent standards and systematic processes to define and develop large projects, assess readiness for construction, measure project performance, and manage the transition to operation.[2] In other words, NSF, through its contracting organizations, has been generally successful in completing major construction projects despite its lack of a clear, systematic approach to managing such projects. Nevertheless, a systematic and transparent approach would help NSF to avoid common pitfalls in large project management in the future—especially as new projects grow in size and complexity—and it would certainly improve NSF's ability to convey project status to stakeholders and to other concerned and responsible parties (especially those in the Congress and the Executive Branch). A new standardized approach would also include open bidding for the large and technologically challenging ground-based initiatives recommended by the decadal surveys. Such open competition for new national facilities would benefit the university community participants that could lead such projects, and the competition would optimize the scientific return on the investments made by NSF. The committee is hopeful that the current NSF self-review requested by the Office of Management and Budget and ongoing government oversight of NSF's large project management can serve to improve the agency's stewardship capabilities in this arena. However, NSF has to do a better job of openly communicating with the Congress about these

[2]An example approaching the type of systematic process that the committee is describing is the process delineated in the *NASA Strategic Management Handbook* ("The Red Book," National Aeronautics and Space Administration, Washington, D.C., 2000). It is available online at <http://www.hq.nasa.gov/office/codez/plans/2000Handbook.pdf>.

large projects from their earliest conceptual stage, including placement in the Major Research Equipment account queue, through to completion of their scientific operation stage.

The committee recognizes that it has posed some significant challenges to NSF: creating policies and structures for building a national optical and infrared observatory system that involves coordination with the private- and state-funded observatories; sharing costs and authority with astronomical institutions in foreign countries; and negotiating with NASA and other federal agencies over investment strategies. NSF must accomplish all of this with constrained budgets and many strong competing needs elsewhere in the science and engineering fields for which NSF has stewardship. Responding to these challenges will require the full support and attention of the National Science Board to policy-level planning and oversight of large astronomy projects, possibly to a greater degree than has been customary.

The Implications of Concentrating All Astronomy and Astrophysics Activity in a Single Agency

NASA and NSF have quite distinct cultures, strengths, and missions, and each contributes distinctively to society. Their diverse approaches add to the vitality of the overall U.S. astronomical and astrophysical research effort. While developing an integrated plan might be easier within a single agency, denying NSF a key independent role in astronomy and astrophysics would seriously weaken the intellectual roots of the discipline and undermine support for the combination of teaching with research that is essential to educating the nation's future scientists. This is too high a price to pay for concentration of astronomy and astrophysics in a single agency. In addition, many NASA space missions had their conceptual origins in university research, and the workforce that carries out all aspects of these missions was trained mainly at these universities. NASA's science productivity would be one of the major casualties if the creativity of university research in astronomy and astrophysics were reduced by a diminished role for NSF.

The Benefits of an Integrated Multiagency Strategy of Research Support

A balanced, integrated strategy for all U.S. astronomy and astrophysics can result in an optimally effective program for the nation. Given the fact that a new coordination and planning process is called for that should bring together all of the federal supporters of astronomy and astrophysics for the first time, the committee believes that the Office of Science and

Technology Policy and the Office of Management and Budget are the proper government entities to supervise the establishment of such a process. They have the necessary government-wide perspective, and they can serve as honest brokers in assisting the agencies to come together. Furthermore such a role is quite consistent with their charters.

An integrated strategy that is (1) rooted in NSF and NASA with the participation of other relevant federal agencies, (2) supervised and approved by the Office of Management and Budget and the Office of Science and Technology Policy, and (3) endorsed by the Congress can result in an optimally effective program for the nation. Currently, there is no national organizational structure charged with formulating an integrated program of space-based and ground-based science and providing the necessary scientific, engineering, and fiscal guidance. The decadal survey provides only a point of departure for such a national strategic plan. An important advantage of an integrated approach is that it would provide a more focused path to the construction and operation of joint projects, whether national or international. An integrated program also provides the best context within which the national agencies can work to ensure that the United States enters and sustains its international collaborations with a clear scientific purpose and a well-considered technical and administrative approach.

RECOMMENDATIONS

The foregoing findings led the committee to make the following recommendations.

1. The National Science Foundation's astronomy and astrophysics responsibilities should not be transferred to NASA.
2. In order to maximize the scientific returns, the federal government should develop a single integrated strategy for astronomy and astrophysics research that includes supporting facilities and missions on the ground and in space.
3. To help bring about an integration of ground- and space-based astronomy and astrophysics, the Office of Science and Technology Policy and the Office of Management and Budget should take the initiative to establish an interagency planning board for astronomy and astrophysics. Input to the planning board from the scientific and engineering community should be provided by a joint advisory committee of outside experts that is well connected to the advisory structures within each agency.

   —The recommended interagency Astronomy and Astrophysics

Planning Board, with a neutral and independent chair to be designated by the Office of Management and Budget in conjunction with the Office of Science and Technology Policy, should consist of representatives of NASA, NSF, the Department of Energy, and other appropriate federal agencies such as the Smithsonian Institution and the Department of Defense. The Planning Board should coordinate the relevant research activities of the member agencies and should prepare and annually update an integrated strategic plan for research in astronomy and astrophysics, addressing the priorities of the most current National Research Council decadal survey of the field in the context of tight discretionary budgets.

—The membership of the Planning Board's advisory committee should be drawn in part from the external advisory panels of the Planning Board's member agencies. The advisory committee should be chaired by an individual who is neither a member of the agency advisory panels nor an agency employee. The committee should participate in the development of the integrated strategic plan and in the periodic review of its implementation.

4. NASA and NSF should each put in place formal mechanisms for implementing recommendations of the interagency Astronomy and Astrophysics Planning Board and integrating those recommendations into their respective strategic plans for astronomy and astrophysics. Both agencies should make changes, as outlined below, in order to pursue effective roles in formulating and executing an integrated federal program for astronomy and astrophysics. These changes should be coordinated through the interagency Planning Board to clarify the responsibilities and strategies of the individual member agencies.
5. The NSF, with the active participation of the National Science Board, should:
   a. Develop and implement its own strategic plan, taking into account the recommendations of the interagency Planning Board. Its strategic plan should be formulated in an open and transparent fashion and should have concrete objectives and time lines. NSF should manage its program in astronomy and astrophysics to that plan, ensuring the participation of scientifically relevant divisions and offices within NSF. To help generate this plan, NSF should reestablish a federally chartered advisory committee for its Astronomical Sciences Division to ensure parity with the NASA advisory structure. The chair of this Astronomical

Sciences Division advisory committee should be a member of the Mathematical and Physical Sciences Directorate advisory committee. Furthermore, the Mathematical and Physical Sciences Directorate advisory committee should make regular written and oral reports of its key findings and recommendations to the National Science Board.

b. Address the outstanding issues that are affecting ground-based astronomy at present.
   —Lead the development of an integrated strategy for assembling the resources needed to build and operate the challenging suite of ground-based initiatives recommended by the most current decadal survey.
   —Work to create an integrated system for ground-based optical/infrared astronomy and astrophysics encompassing private, state, and federally funded observatories, as advocated by the decadal survey.
   —Improve and systematize the process for initiating, constructing, managing, and using ground-based facilities, so that it includes:
   - clear lines of authority for negotiations, particularly those involving international partners,
   - an open bidding process for contracts,
   - comprehensive budgeting that provides for all aspects and phases of projects, and
   - provision of the resources required to exploit the scientific potential of the facilities, including associated instrumentation, theoretical work, data analysis, and travel.

c. Undertake a more concerted and well-funded effort to inform the press and the general public of scientific discoveries, and cooperate with NASA in developing a coordinated public information program for astronomy and astrophysics.

6. In parallel, NASA should:
   a. Implement operational plans to provide continuity of support for the talent base in astronomy and astrophysics should critical space missions suffer failure or be terminated.
   b. Continue and enlarge its program of research support for proposals from individual principal investigators that are not necessarily tied to the goals of specific missions.
   c. Support critical ground-based facilities and scientifically enabling precursor and follow-up observations that are essential to the success of space missions. Decisions on such support

should be considered in the context of the scientific goals articulated in the integrated research plan for astronomy and astrophysics.

d. Cooperate with NSF in developing a coordinated public information program for astronomy and astrophysics.

Appendixes

A

Biographies of Committee Members and Key NRC Staff

COMMITTEE MEMBERS

NORMAN R. AUGUSTINE (*Chair*) retired in 1997 as chair and CEO of Lockheed Martin Corporation (LMC). Prior to the formation of Lockheed Martin, he served as chair and CEO of the Martin Marietta Corporation. After retiring from LMC, he served as a member of the faculty of the Department of Mechanical and Aerospace Engineering at Princeton University. In 1965, he served in the Pentagon in the Office of the Secretary of Defense. In 1973, he returned to government as assistant secretary of the Army and in 1975 became under secretary. Mr. Augustine has served as chairman of numerous committees, boards, and advisory panels for the government and has been a member of the Board of Directors of the Planetary Society. He has been awarded numerous medals, including the National Medal of Technology and, on five occasions, the Department of Defense's highest civilian decoration, the Distinguished Service Medal. He is a former chair of the National Academy of Engineering and a former president of the American Institute of Aeronautics and Astronautics, and he has served on the President's Council of Advisors on Science and Technology. He holds eighteen honorary doctorate degrees.

LEWIS M. BRANSCOMB is the emeritus Aetna Professor of Public Policy and Corporate Management and emeritus director of the Science, Technology, and Public Policy Program in the Center for Science and International Affairs at Harvard University's Kennedy School of Government.

He was a research physicist at the National Bureau of Standards (now the National Institute of Standards and Technology) and also served as its director. Dr. Branscomb was the founder and first director of the Joint Institute for Laboratory Astrophysics at the University of Colorado, and was an at-large director of the Associated Universities for Research in Astronomy. He served on the President's Science Advisory Committee, chairing the PSAC Committee on Space Science and Technology during Project Apollo. He served as vice president and chief scientist of IBM Corporation until his retirement from IBM in 1986. Dr. Branscomb is a former president of the American Physical Society and of Sigma Xi, the Scientific Research Society.

CLAUDE CANIZARES is the Bruno Rossi Professor of Experimental Physics at the Massachusetts Institute of Technology and director of the Center for Space Research. He is a principal investigator on NASA's Chandra X-ray Observatory, leading the development of the High Resolution Transmission Grating Spectrometer for this major space observatory, and is associate director of the Chandra X-ray Observatory Center. He has also worked on several other space astronomy missions, including as co-investigator on the Einstein Observatory (HEAO-2). His main research interests are high-resolution spectroscopy and plasma diagnostics of supernova remnants and clusters of galaxies, cooling flows in galaxies and clusters, x-ray studies of dark matter, x-ray properties of quasars and active galactic nuclei, and gravitational lenses. He served on the NASA Advisory Council and was chair of the NRC's Space Studies Board. Dr. Canizares is a member of the National Academy of Sciences, a Fellow of the American Physical Society, a member of the International Academy of Astronautics, and a fellow of the American Association for the Advancement of Science.

SANDRA FABER is a professor of astronomy and astrophysics at the University of California at Santa Cruz and an astronomer at the University of California Observatories/Lick Observatory. Dr. Faber's research is conducted on the structure and origin of galaxies, the origin of structure in the universe, the nature of the Big Bang, the formation of the Milky Way, distributions and motions of nearby galaxies in space, design and construction of modern, large optical telescopes, and optical instrumentation for astronomy. She is currently the principal investigator for the Deep-Imaging Multiobject Spectrograph Project on the second Keck Telescope and was formerly involved with the Hubble Space Telescope's Wide Field Camera I. She was co-chair of the Keck Science Steering Committee during the Keck Telescope construction and is a trustee of the Carnegie Institution of Washington. Dr. Faber has been a leader in developing a physical understanding of the formation and evolution of galaxies, beginning with her development of the means for decomposing the spectra of galaxies into their component stellar populations. She is a former member of the NRC Panel on Cosmology, the Committee on Astronomy and Astrophysics, and the Committee on the Physics of the Universe.

ROBERT D. GEHRZ is a professor of physics and astronomy and director of the observatories at the University of Minnesota. From 1972 until 1985, Dr. Gehrz was on the faculty of the Department of Physics and Astronomy of the University of Wyoming, where he and John A. Hackwell built the Wyoming Infrared Observatory with funds they obtained from the State of Wyoming and the National Science Foundation. His primary research contributions are on the physical properties of astrophysical grains in interstellar, circumstellar, and solar system environments, the physics of nova explosions and their chemical contributions to the interstellar medium, the physical characteristics of the circumstellar ejecta of luminous stars, the infrared morphology of regions of star formation, and the infrared activity of comet nuclei. In addition to his research effort in ground-based observations and instrumentation development, Dr. Gehrz has obtained space astronomy observations with the European Space Agency's Infrared Space Observatory and NASA observatories including the International Ultra-Violet Explorer, the Kuiper Airborne Observatory, Hubble Space Telescope, and the Chandra X-ray Observatory. Dr. Gehrz is a member of the Science Working Group for NASA's Space Infrared Telescope Facility (SIRTF) for which he performs facility scientist duties and leads the SIRTF Community Task Force. Dr. Gehrz was elected a fellow (nonresident) of the Explorer's Club in 1979 and a fellow of the American Association for the Advancement of Science in 1995. He was the chair and a member of the Board of the International Gemini Project from 1996 to 1999 and was president of the American Astronomical Society from 1998 to 2000. He has been a member of the AURA Board (director-at-large), the Astronomy and Astrophysics Survey Committee (Field Committee), the Committee for Planetary and Lunar Exploration, the NSF Astronomy Advisory Committee, and NASA's Space Science Advisory Committee. Dr. Gehrz has also chaired or served as a member of numerous other committees and advisory panels for government agencies, national laboratories, and universities.

PHILIP R. GOODE is director of the Big Bear Solar Observatory at Big Bear Lake, California; Distinguished Professor of Physics and Mathematics at the New Jersey Institute of Technology; and a visiting associate in physics, mathematics, and astronomy at the California Institute of Technology. His primary research interests are in solar physics and global climate change. These include the internal structure of the Sun, the nature of the Sun's magnetic fields, flares, coronal mass ejections, and space weather. He is also measuring and modeling Earth's reflectance from studies of earthshine and satellite cloud cover data, respectively. Dr. Goode was a member of the NRC Panel on Solar Astronomy (1998-2000), which advised the Astronomy and Astrophysics Survey Committee on scientific opportunities and priorities in the field of solar astronomy, and is currently a member of the survey committee for the NRC study on solar and space physics. He served on the most recent Committee of Visitors for NSF's Astronomical Sciences Division.

BURTON RICHTER, the Paul Pigott Professor in the Physical Sciences at Stanford University, was jointly awarded the 1976 Nobel Prize for Physics with Samuel C.C. Ting for the discovery of a new subatomic particle, the J/psi particle. In 1956, he became a research associate at Stanford University, becoming a full professor in 1967. His research has focused on quantum electrodynamics, elementary particles, and accelerator physics. In 1973, he completed construction of the Stanford Positron-Electron Asymmetric Ring, a colliding-beam accelerator with which he discovered a new subatomic particle, the first of a new class of very massive, long-lived mesons. Dr. Richter was later instrumental in the conception and construction of the Stanford Linear Accelerator Center Linear Collider, where he served as technical director, becoming director in 1984 and then returning to research in 1999. Dr. Richter is a past president of the American Physical Society and is currently president of the International Union of Pure and Applied Physics.

ANNEILA I. SARGENT is a professor of astronomy at the California Institute of Technology, as well as director of the Owens Valley Radio Observatory and of the Interferometry Science Center at Caltech. Her research concentrates on observational studies of star and planet formation. Dr. Sargent has chaired NASA's Space Science Advisory Committee and served on the NASA advisory council. She has also served on the advisory committee for the National Science Foundation's Mathematical and Physical Sciences Directorate. She was a member of the most recent Astronomy and Astrophysics Survey Committee. Currently, Dr. Sargent is president of the American Astronomical Society and is a member of the NRC's Board on Physics and Astronomy. She is an associate of the Royal Astronomical Society.

FRANK H. SHU is a professor of astronomy, University of California at Berkeley, and University Professor, University of California. His research concerns the astrophysical processes of star formation, the dynamics and structure of galaxies, the physics of the interstellar medium, and planetary system formation. He is the recipient of the 1977 Warner Prize of the American Astronomical Society, the 1996 Brouwer Award of the Division of Dynamical Astronomy of the American Astronomical Society, and the 2000 Dannie Heineman Prize of the American Astronomical Society and the American Institute of Physics. Prof. Shu serves as co-chair of the science working group for NASA's Terrestrial Planter Finder project, a member of the Center for Star Formation Studies (NASA Astrophysics Theory Program), and a member of National Optical Astronomy Observatory's science working group on the Giant Segmented Mirror Telescope project. He is a member of the Center for Integrative Planetary Science at the University of California at Berkeley and is chair of the advisory panel for Academia Sinica's Institute of Astronomy and Astrophysics. Prof. Shu served on the 1983 Astronomy Survey Committee and was a member of the U.S. National Committee for the International Astronomical Union. He was a member of the 2001 Astronomy and Astrophysics Survey Committee's Panel on Astronomy Education and Policy. He is a past president of the American Astronomical Society.

MAXINE FRANK SINGER is the president of the Carnegie Institution of Washington and Scientist Emeritus at the National Cancer Institute, National Institutes of Health, Bethesda, Maryland. Prior to coming to Carnegie in 1988, she was chief of the Laboratory of Biochemistry, Division of Cancer Biology and Diagnosis at the National Cancer Institute, where she conducted research in biological chemistry and molecular genetics. At the Carnegie Institution, Dr. Singer oversees the operations and research of five renowned scientific research laboratories, including the Carnegie Observatories and its telescopes at Las Campanas, Chile. She also has instituted a community outreach and education program that brings leading scientific speakers to the community and trains local science teachers. Dr. Singer is a member of various advisory panels to scientific societies, the government, and academia. Currently she chairs the Academies' Committee on Science, Engineering, and Public Policy and serves on the NASA Astrobiology Institute Scientific Advisory Board.

ROBERT WILLIAMS is currently the Distinguished Research Scholar of the Space Telescope Science Institute (STScI) in Baltimore, Maryland, having served as director of the Institute from 1993 to 1998. The Institute, together with Goddard Space Flight Center, operates the orbiting Hubble Space Telescope for NASA. Before assuming his present position Dr. Williams spent 8 years in Chile as director of the Cerro Tololo Inter-American Observatory, the national observatory of the United States in the southern hemisphere. He was a Senior Fulbright Professor at the

University of London from 1971 to 1972 and received the Alexander von Humboldt Award from the German government in 1991. Dr. Williams' research has focused on exploding stars and diffuse gas clouds in space, and he has been a strong advocate of public outreach for science. In 1998 he was awarded the Beatrice Tinsley Prize of the American Astronomical Society for his leadership of the Hubble Deep Field project, which used the Hubble Telescope to study distant galaxies in the early universe. For this project, he was awarded the NASA Distinguished Public Service Medal in 1999.

NRC STAFF

JOSEPH K. ALEXANDER, JR., has been director of the NRC Space Studies Board since February 1998. Mr. Alexander served as deputy assistant administrator for science in the Environmental Protection Agency's Office of Research and Development from 1994 to 1998. Prior to joining EPA, he spent 32 years at NASA as associate director of space sciences at the Goddard Space Flight Center (1993-1994), assistant associate administrator for space sciences and applications in the Office of Space Science and Applications (1987-1993), acting director of life sciences (1992-1993), deputy NASA chief scientist (1985-1987), and senior policy analyst at the White House Office of Science and Technology Policy (1984-1985). Prior to those assignments he conducted basic research in astronomy, planetary exploration, and space physics (1962-1984).

JOEL R. PARRIOTT is a senior program officer at the NRC's Board on Physics and Astronomy. Dr. Parriott came to the NRC in 1998 after receiving his Ph.D. in astronomy and astrophysics from the University of Michigan. His research, for which he received the Ralph B. Baldwin Prize from the University of Michigan, involved gas dynamics in elliptical galaxies and high-performance parallel computing. In addition to serving as the study director for this report, Dr. Parriott is the staff officer for the Astronomy and Astrophysics Survey Committee, the Committee on the Physics of the Universe, and the Committee on Astronomy and Astrophysics.

DONALD C. SHAPERO received the B.S degree from the Massachusetts Institute of Technology in 1964 and the Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., he became a Thomas J. Watson Postdoctoral Fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the National Research Council in 1975. He took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy. As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Physical Society, the American Astronomical Society, and the International Astronomical Union. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

B

Meeting Agendas

FIRST MEETING

June 13-14, 2001
Holiday Inn Georgetown
Washington, D.C.

Wednesday, June 13, 2001

Closed Session

8:00 am Convene; introductions; goals for the meeting
—Norman Augustine, Chair

Open Session

9:00 am Public introductions; study/meeting plan
—Norman Augustine

9:15 am White House discussion; purpose of this study and charge to the committee
—Richard Russell, Chief of Staff, Office of Science and Technology Policy
—Marcus Peacock, Associate Director, Natural Resource Program, Office of Management and Budget

10:00 am	Break
10:30 am	Sponsoring agency discussion Future role of astronomy and astrophysics; management philosophy for science individual investigator grants and science projects/missions; interagency cooperation in addressing science questions of mutual interest —Daniel Goldin, Administrator, NASA —Edward Weiler, Associate Administrator, Office of Space Science, NASA —Joseph Bordogna, Deputy Director, NSF —Wayne Van Citters, Acting Director, Astronomical Sciences Division, NSF
Noon	Lunch
1:00 pm	Insights based on recent NRC reports –*Federal Funding of Astronomical Research* —John Huchra, Harvard-Smithsonian Center for Astrophysics, Co-chair, NRC Committee on Astronomy and Astrophysics –*Astronomy and Astrophysics in the New Millennium* —Joseph H. Taylor, Princeton University, Co-chair, NRC Astronomy and Astrophysics Survey Committee
2:00 pm	Managing international participation in major ground-based projects and programs: Reflections of a former European Southern Observatory Director General —Riccardo Giacconi, Associated Universities, Inc.
2:30 pm	Professional society perspectives –American Astronomical Society —Marcia Rieke, University of Arizona –Solar Physics Division —Judy Karpen, Naval Research Laboratory –High Energy Astrophysics Division —Alice Harding, NASA Goddard Space Flight Center –Division for Planetary Sciences —Mark Sykes, University of Arizona Small undergraduate college perspective —Frank Winkler, Middlebury College
3:45 pm	Break
4:15 pm	Smithsonian Institution: Overview and role in supporting research in astronomy and astrophysics —Irwin Shapiro, Director, Harvard-Smithsonian Center for Astrophysics

4:45 pm	Private observatory perspective: Management and funding of private observatories —Joseph Miller, University of California, Santa Cruz, Director, University of California Observatories/Lick Observatory
5:15 pm	Public comment session —David Helfand, Columbia University

Closed Session

6:15 pm	Committee deliberations
7:00 pm	Adjourn for the day

Thursday, June 14, 2001

Open Session

8:00 am	Reconvene —Norman Augustine Views of former agency managers: Management experiences; interagency cooperation —NASA: Lennard Fisk, University of Michigan —NSF: William Harris, University of South Carolina
9:00 am	NSF Management Organization Roundtable Initial statements; discussion; question-and-anser session –Association of Universities for Research in Astronomy, Inc. —William Smith, President –Associated Universities, Inc. —Riccardo Giacconi, President –National Astronomy and Ionosphere Center —Paul Goldsmith, Director –National Center for Atmospheric Research —Tim Killeen, Director –Laser Interferometer Gravitational-wave Observatory Laboratory —Gary Sanders, Deputy Director
10:40 am	Break
11:10 am	Congressional perspective: House Science Committee —Sharon Hays, Staff Director, Research Subcommittee

Closed Session

11:30 am Working lunch
Needs of astronomy and astrophysics?
—Norman Augustine
1:00 pm Adjourn

SECOND MEETING

July 12-13, 2001
Stanford Linear Accelerator Laboratory
Menlo Park, California

Thursday, July 12, 2001

Closed Session

8:00 am Convene
—Claude Canizares, Acting Chair

Open Session

9:00 am Perspective on astronomy at NSF
—Robert Eisenstein, Assistant Director, NSF Mathematical and Physical Sciences Directorate
9:30 am NSF-DOE joint committee structure: Nuclear Science Advisory Committee
—Ernest Moniz, Massachusetts Institute of Technology (by telephone)
10:00 am Break
10:15 am National Observatories discussion
–National Radio Astronomy Observatory
—Paul Vanden Bout, Director (by telephone)
–National Optical Astronomy Observatory
—Jeremy Mould, Director
–National Solar Observatory
—Steven Keil, Director (by telephone)
11:15 am Lunch

Closed Session

Noon Committee deliberations
—Claude Canizares

Open Session

2:00 pm NSF director's perspective
—Rita Colwell, Director, NSF
2:30 pm Break
2:45 pm Gemini Observatory: past/current project management and international program issues
—Matt Mountain, Director

Closed Session

3:15 pm Continue deliberations
—Claude Canizares
6:00 pm Adjourn for the day

Friday, July 13, 2001

Closed Session

8:00 am Reconvene; continue deliberations
—Claude Canizares

Open Session

11:30 am Department of Energy's role in supporting astrophysics: boundaries, funding and facilities, strategic planning, high-energy physics community research trends
—Peter Rosen, Associate Director, DOE Office of High Energy and Nuclear Physics (by telephone)
—P.K. Williams, Senior Program Officer, DOE Division of High Energy Physics (by telephone)
—Jim Stone, Physicist, DOE Division of High Energy Physics (by telephone)

Closed Session

Noon	Working Lunch —Claude Canizares
1:00 pm	Adjourn

THIRD MEETING

July 31 – August 1, 2001
National Research Council
Washington, D.C.

This meeting was closed in its entirety.

Tuesday, July 31, 2001

8:00 am	Convene Committee deliberations and report drafting —Norman Augustine, Chair
6:00 pm	Adjourn for the day

Wednesday, August 1, 2001

8:00 am	Reconvene Committee deliberations and report drafting —Norman Augustine
1:00 pm	Adjourn

C

The Current Astronomy and Astrophysics Enterprise

NATIONAL SCIENCE FOUNDATION

The National Science Foundation provides support for astrophysical research in optical/infrared astronomy, radio astronomy, solar physics, and planetary astronomy, and in particle and gravitational-wave astrophysics, via (1) awards for principal investigator grants, (2) instrumentation development, (3) major facility construction, and (4) facility operations. A snapshot of recent funding levels is presented in Table C.1, and selected funding trends are shown in Figures C.1 through C.7.[1]

Research and teaching funding for the discipline comes primarily from the Astronomical Sciences Division (AST) in the Mathematical and Physical Sciences (MPS) Directorate, with additional support from other parts of MPS (especially for particle astrophysics and gravitational-wave research), the Division of Atmospheric Sciences (for solar physics), the Office of Polar programs (for astronomy from Antarctica), the Directorate

NOTE: See Figure 1.1 for a schematic depiction of the U.S. astronomy and astrophysics research enterprise. All of the information presented here can be found in much greater detail in *Federal Funding of Astronomical Research* (National Academy Press, Washington, D.C., 2000).

[1]Unfortunately, due to the rapid time scale for this study, combined with the difficulty of obtaining appropriate data, the committee was not able to update these plots using the most recent funding data.

TABLE C.1 NSF Astronomy Division Funding Data from FY 2000 (Thousands of Current-Year Dollars)

Budget Category	Dollars	Percentage of Budget
Research	33,200	24
Operations	88,000	64
Construction and instrumentation	16,800	12
Total	138,000	100

SOURCE: NSF's Astronomical Sciences Division.

for Education and Human Resources (for some undergraduate and graduate education), Crosscutting/Interdisciplinary Programs, and the Office of Integrative Activities. NSF supports the operation of six major national observing centers—the National Optical Astronomy Observatory, with facilities in Arizona and Chile; the National Radio Astronomy Observatory, with facilities in New Mexico, West Virginia, Virginia, and Arizona;

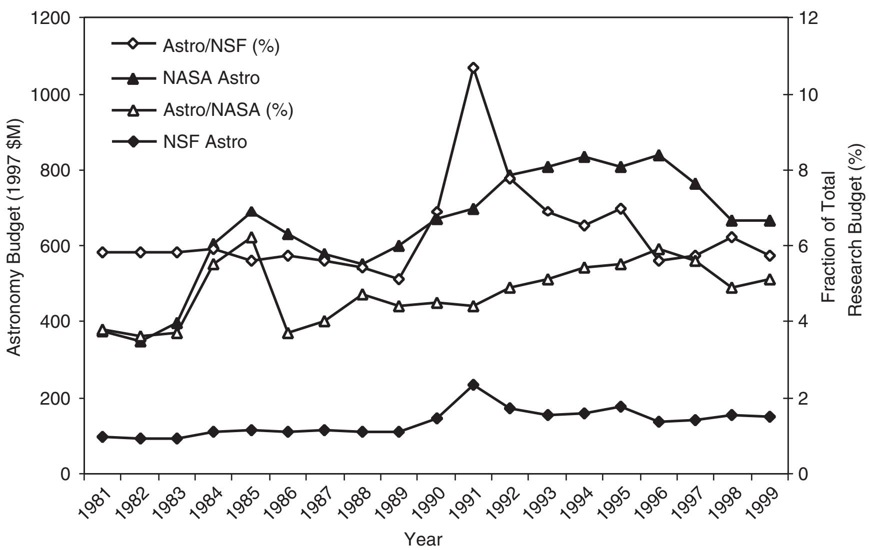

FIGURE C.1 Overall funding of astronomy by NASA and NSF. Astro/NSF and Astro/NASA are the relative fractions of the NSF and NASA research and development budgets allocated to astronomy and astrophysics research (right-hand scale).
SOURCE: After Figure 2.2 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 8.

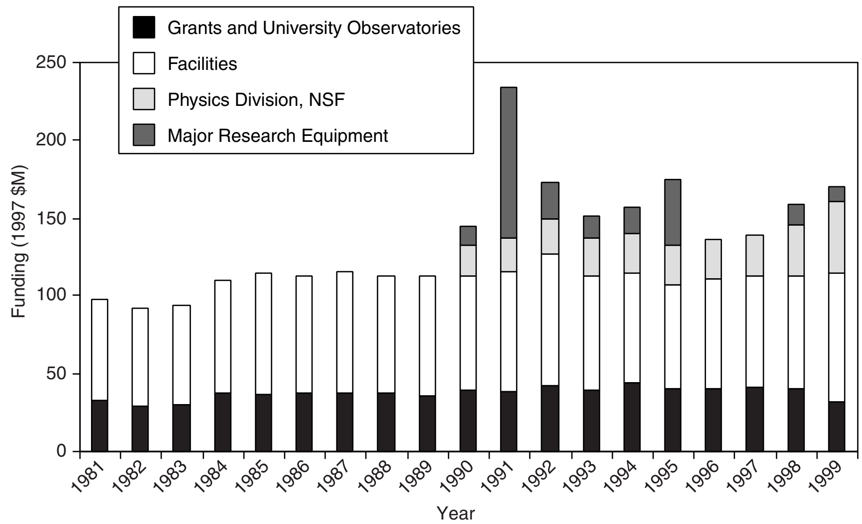

FIGURE C.2 NSF funding for astronomy. Note that funding for university observatories is grouped with that for grants, as in the 1991 Decadal Report.
NOTE: Major research equipment (MRE) bars include funding for the Green Bank Telescope in 1991. The funding denoted by PHY includes support for astrophysics and astronomy programs in NSF's Physics Division. Data on Physics Division support for astronomy and astrophysics were not available for the years prior to 1990. Funding for the Laser Interferometer Gravitational-wave Observatory is not included in either the MRE or the PHY category in this figure.
SOURCE: After Figure 2.3 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 9.

the National Astronomy and Ionosphere Center, which operates the Arecibo Telescope in Puerto Rico; the international Gemini Observatory, with telescopes in Hawaii and Chile; the National Solar Observatory, with telescopes in New Mexico and Arizona; and the Laser Interferometer Gravitational-wave Observatory, with installations in Washington and Louisiana. NSF also supports the High Altitude Observatory in Colorado through the National Center for Atmospheric Research. NSF is the major source of support for millimeter-wave astronomy in the United States through four university radio observatories. The NSF astronomy program is entirely extramural. According to NSF officials, the AST program had approximately 500 active grants in FY 2000, and those contributed to the support of over 450 senior researchers, more than 100 postdoctoral scientists, and more than 500 graduate and undergraduate students.

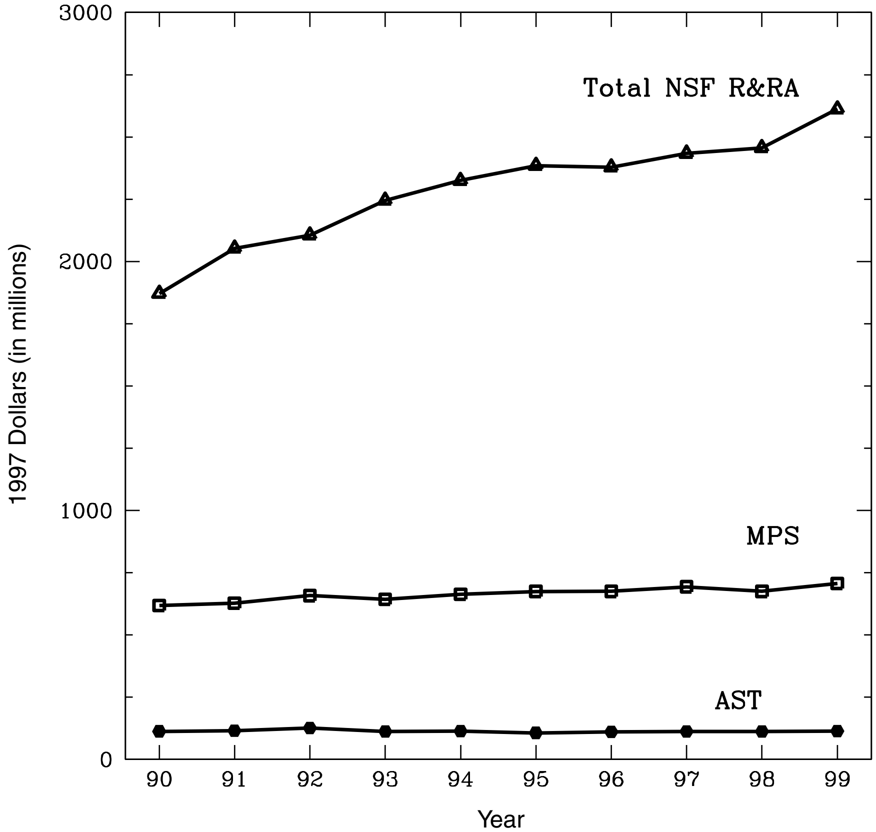

FIGURE C.3 Total NSF, Mathematical and Physical Sciences Directorate (MPS), and Astronomical Sciences Division (AST) funding, FY 1990-1999, in 1997 dollars. Top curve is the total NSF R&RA budget (R. Konkel, from NSF Congressional Budget Summary) and does not include construction. Lower curves are for the MPS Directorate and the AST, also excluding construction (MRE) funding; these lines represent the essential "operating" budgets of the Mathematical and Physical Sciences Directorate and the Division of Astronomical Sciences.
SOURCE: After Figure 5.1 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 27.

Awards for work in solar astronomy from areas other than AST amount to about 130 additional grants to the NSF total (National Research Council, *Ground-based Solar Research: An Assessment and Strategy for the Future*, National Academy Press, Washington, D.C., 1998) with a commensurate increase in the size of the investigator and student population being affected by NSF research grants.

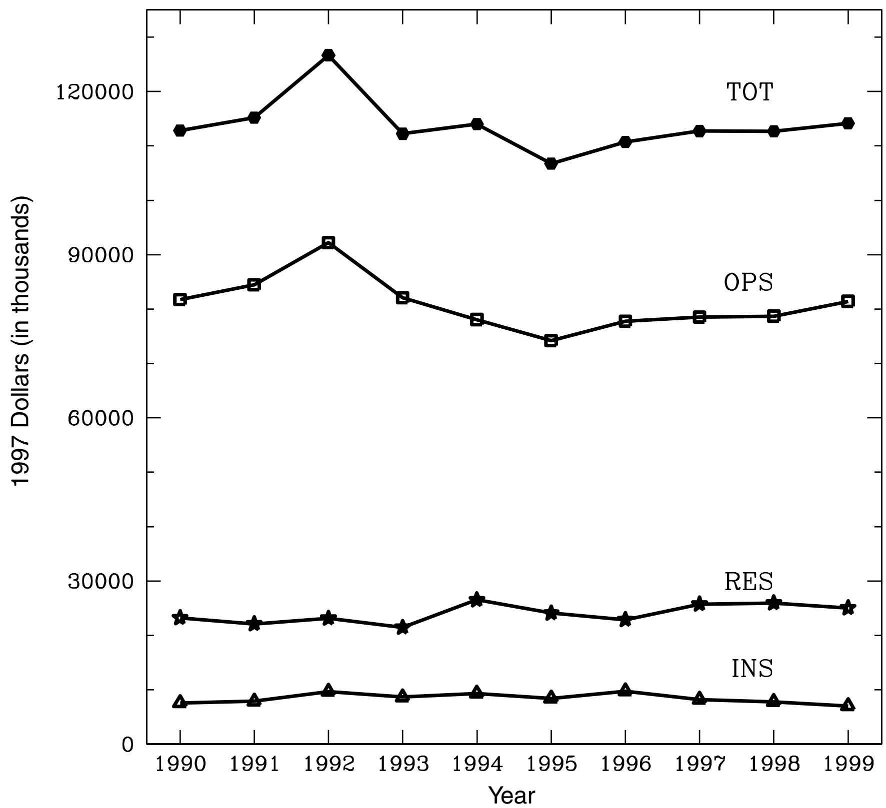

FIGURE C.4 NSF Division of Astronomical Sciences budget in 1997 dollars. The top curve is the total AST budget. Lower curves are for total operations (OPS), research grants (RES), and instrumentation grants (INS) expenditures. Operation of private radio facilities is included in the operations line. The AST budget line does not include major construction funding under the MRE program.
SOURCE: After Figure 5.2 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 33.

NASA

NASA support for research in astronomy and astrophysics includes funding for the development of space observatories and instruments on other space missions that conduct astronomical measurements, space mission operations and data processing, research grants for data analysis and other astronomical and astrophysical studies, and other activities in support of space astronomy. Included in the latter category are some ground-

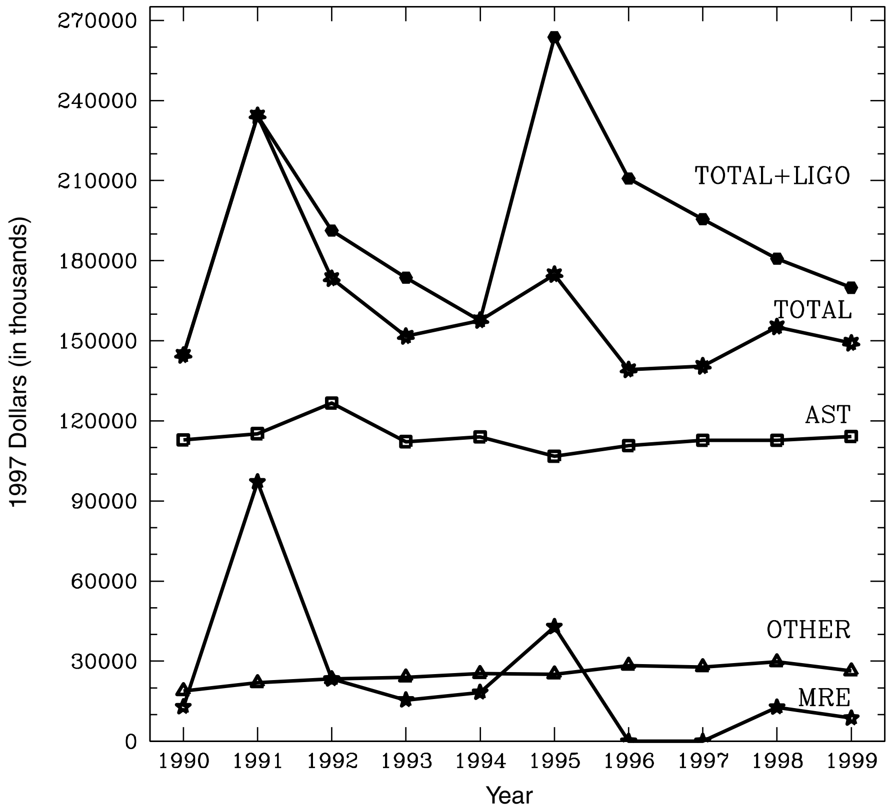

FIGURE C.5 Total NSF budget for astronomy and astrophysics in 1997 dollars, 1990 to 1999. The top curve is the total of the budget for AST, MRE, other, and LIGO. LIGO support is included in this total, but not in astronomy-related MRE, since this is primarily a physics program. The next curve down is the total of AST, MRE, and other budget, without LIGO. Lower curves show the breakouts for AST; astronomy-related MRE, including the VLBA, GBT, Gemini, and ALMA but not LIGO; and other support for astronomy and astrophysics from MPS, OPP, ATM, and OMA.
SOURCE: After Figure 5.3 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 34.

based observatories (most U.S. planetary astronomy), some balloon and sounding rocket projects, and data archival centers. Among the major ground-based facilities or programs to which NASA has contributed some support are the Keck Interferometer Project, the Infra-Red Telescope Facility on Mauna Kea, the 2-Micron All Sky Survey, and the Sloan Digital Survey. A snapshot of recent NASA funding levels is given in Table C.2,

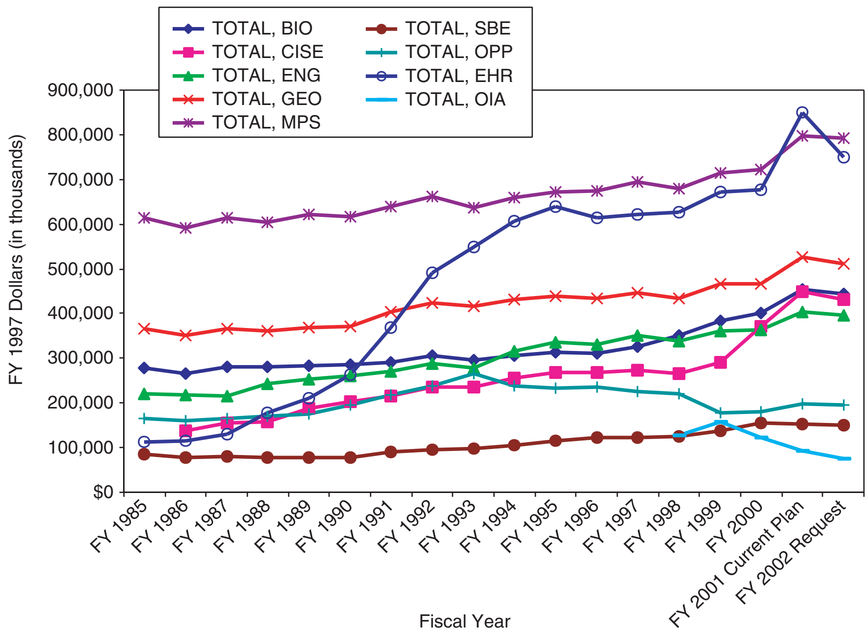

FIGURE C.6 NSF Directorate funding since 1985 (in thousands of FY 1997 dollars).
SOURCE: Data from NSF.

and some funding trends are shown in Figures C.1 and C.8. NASA support for astronomy and astrophysics research resides entirely under the Office of Space Science. In addition to support for research in the extramural scientific community, NASA supports researchers in many of its field installations, all via competitive peer review. According to NASA officials, NASA's astronomy and astrophysics programs, including solar and planetary astronomy, include approximately 2500 research grants. NASA officials estimated that those grants involve participation by more than 800 senior researchers, nearly 1000 postdoctoral associates, and more than 900 (mostly graduate) students.

DEPARTMENT OF ENERGY

Over the past two decades, the Department of Energy (DOE) has become an important provider of funding for astrophysics, including both university and laboratory groups and large projects. DOE funding for astrophysics comes from the Divisions of High-Energy Physics (HEP) and

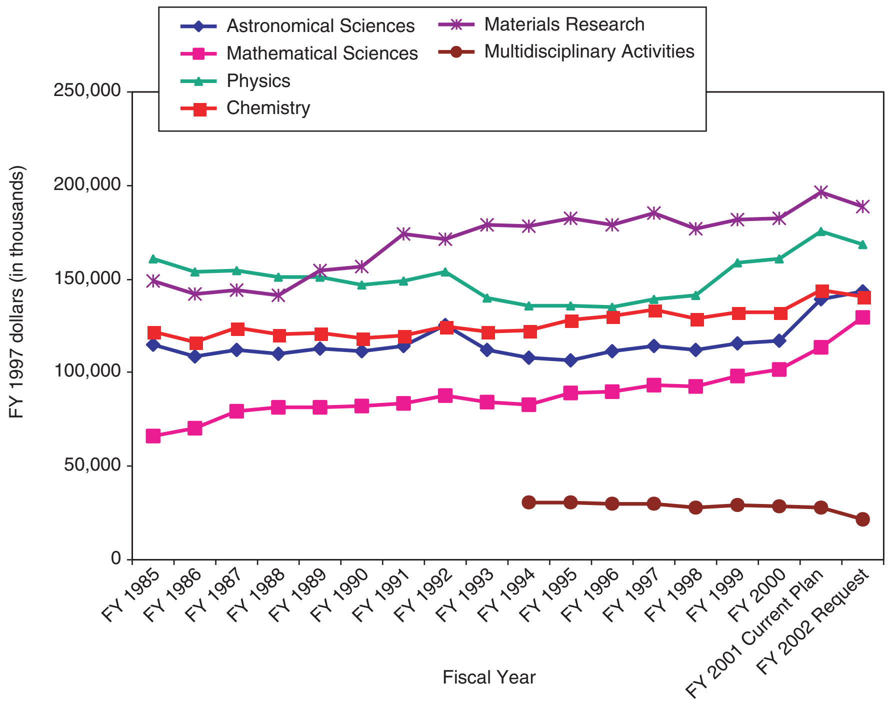

FIGURE C.7 Division budgets since 1985 (in thousands of FY 1997 dollars) within NSF's Mathematical and Physical Sciences Directorate.
SOURCE: Data from NSF.

Nuclear Physics. Total spending was estimated to be $30 million in FY 1997. The HEP program supports university and laboratory groups through continuing grants and contracts and additional money for major projects. In FY 1997, 230 groups were supported at 100 universities. The total budget for this effort was about $13 million, of which about $2.3 million was designated for equipment for the shuttle/space station-based antimatter search, Super Kamiokande (solar, atmospheric, and supernova neutrino and proton decay detector), and MILAGRO and Granite (high-energy gamma-ray detectors). Approximately $12 million was spent at DOE laboratories on astrophysics. Fermilab, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Stanford Linear Accelerator Center all have significant efforts in astrophysics. The Division of Nuclear Physics supports several theoretical nuclear astrophysics groups as well as three solar-neutrino experiments.

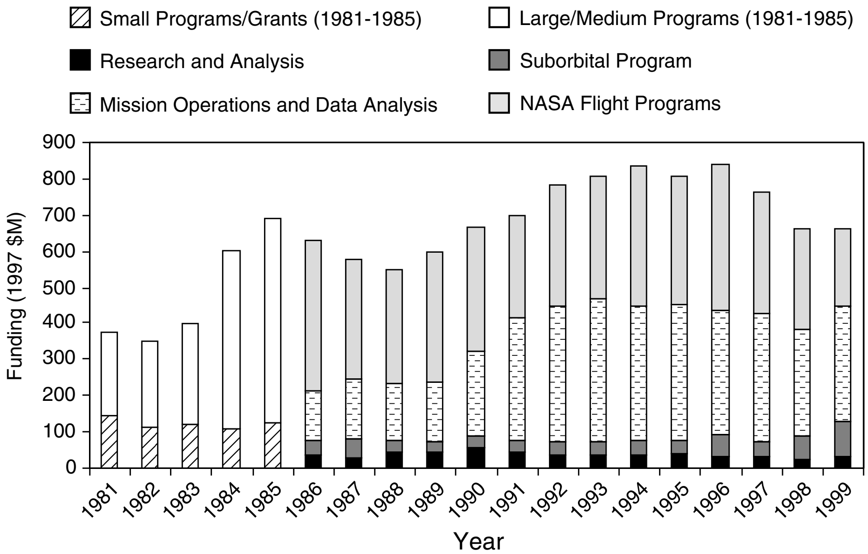

FIGURE C.8 NASA astronomy budget.
SOURCE: After Figure 2.5 in *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000), p. 11.

SMITHSONIAN INSTITUTION

The Smithsonian Institution is an independent trust instrumentality of the United States, which also supports a significant astronomy and astrophysics research endeavor, primarily through the Smithsonian Astrophysical Observatory. The program includes support of two major facilities—the F.L. Whipple Observatory, which includes the Multiple Mirror Telescope (jointly operated with the University of Arizona) and the Submillimeter Array on Mauna Kea, currently under development. The conversion of the Multiple Mirror Telescope to a single 6.5-meter telescope, the construction of the Submillimeter Array, and the major instrumentation programs for each are currently covered separately from the basic operations and research budget. The budget for the Smithsonian Astrophysical Observatory in FY 1997 was approximately $16.8 million plus $7.24 million for major facility construction.

DEPARTMENT OF DEFENSE

Department of Defense funding of astronomy and astrophysics is difficult to determine because it is generally distributed throughout a

TABLE C.2 NASA Astronomy Funding Data from FY 2000 (Thousands of Current-Year Dollars)

Budget Category	Dollars	Percentage of Budget
Research and data analysis	181,000	20
Operations and non-user data analysis	113,000	12
Construction and instrumentation	623,000	68
Total	917,000	100

SOURCE: NASA's Office of Space Science.

number of different DOD programs. The report *Federal Funding of Astronomical Research* (National Research Council, National Academy Press, Washington, D.C., 2000) identified programs with significant federal funding under the U.S. Naval Observatory, Naval Research Laboratory, Air Force Phillips Laboratory, Aerospace Corporation, Sacramento Peak Observatory/National Solar Observatory, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and National Reconnaissance Office.

INDEPENDENT GROUND-BASED OBSERVATORIES

The private and state observatories dominate the public observatories in optical/infrared ground-based astronomy in terms of access to large telescopes: the private/state observatories control roughly 80 percent of the telescope "glass" available to U.S. astronomers. The largest of these telescopes are summarized in Table C.3, including the NSF-supported Gemini Observatory (which is in effect equivalent to one 8-meter telescope because the United States controls about 50 percent of that international observatory). The committee obtained[2] rough FY 2001 funding estimates for the nine major independent observatories,[3] which are shown in Table C.4.

Not all of the private and state observatories provided information,

[2]Courtesy of an informal survey and estimation conducted for the committee by John P. Huchra, Harvard-Smithsonian Center for Astrophysics.

[3]Palomar Observatory, California Association for Research in Astronomy (Keck Observatory), Carnegie Observatories, Steward Observatory, Astrophysical Research Consortium, Harvard-Smithsonian Center for Astrophysics, McDonald Observatory, Lick Observatory, and Mauna Kea Observatory.

TABLE C.3 Optical/IR Telescopes of Aperture >5 Meters Currently Accessible to U.S. Astronomers or Under Construction

Name	% U.S.	Year	Aperture (m)	Capital Cost (millions of dollars)[a]	Instrumentation (millions of dollars)[a]	Location
Keck I	100	1993	10	94	13.5	Hawaii
Keck II	100	1996	10	78	28.1	Hawaii
HET	90	1998	9	17	3.6	Texas
MMT[b]	100	2000	6.5	23	26	Arizona
Gemini-North[c]	52	1999	8	86	11.2	Hawaii
Gemini-South[c]	42	2001	8	86	7.6	Chile
Magellan I	90	2000	6.5	38	9	Chile
Magellan II	90	2002	6.5	36	9	Chile
LBT	50	2002	2 × 8.4	77	13	Arizona
SALT	12	2002	10	17		South Africa

[a]Costs are the total construction and current integrated instrumentation budgets, including the U.S. share.

[b]The MMT capital cost is for the conversion from 4.5-meter only.

[c]Gemini instrumentation costs are those included in the original capital construction budget. Gemini has a separate line for new instrumentation that is included in its annual operations budget.

SOURCE: After Table 5.13 in *Federal Funding of Astronomical Research* (National Academy Press, Washington, D.C., 2000), p. 51.

TABLE C.4 Estimated FY 2001 Spending by the Nine Major Independent Observatories with an Averaged Annual Construction Expenditure for the 1990s (Thousands of Current-Year Dollars)

Funding Category	Dollars	Percentage of Funding
Research support (salaries)	23,000	21
Operations	35,000	33
Construction[a] and development (new instrumentation, upgrades)	50,000	46
Total	108,000	100

[a]This is an estimate of the average expenditure per year based on the integrated total for the decade 1991 to 2000. It includes the federal contribution (through the Smithsonian Insitution) for the Multiple Mirror Telescope conversion but does not include the $36 million that NASA provided for the Keck Interferometer Project.

SOURCE: John Huchra, Harvard-Smithsonian Center for Astrophysics.

and some of those that did specifically asked that their information be used in providing to the committee only integrated totals for the aggregate costs, so these estimates are very rough. There are also other, smaller private optical observatories, such as Michigan-Dartmouth-MIT Observatory, Lowell Observatory, Monterey Institute for Research in Astronomy, Southeastern Association for Research in Astronomy, and so on, which operate telescopes in the 2-meter or smaller class.

The committee did not obtain funding data for the private and state radio observatories, although many of those numbers can be found in *Federal Funding of Astronomical Research*. The main private and state radio observatories include the Five College Radio Observatory; the Caltech Submillimeter Observatory; the Berkeley, Illinois, Maryland Association (BIMA) array; the Owens Valley Radio Observatory (OVRO); and the Haystack Observatory. BIMA and OVRO will soon be combined to form the Combined Array for Research in Millimeter-wave Astronomy.

Details on solar astronomy observatories in the United States (both private/state and public) can be found in *Ground-Based Solar Research: An Assessment and Strategy for the Future* (National Academy Press, Washington, D.C., 1998).

SELECTED INTERNATIONAL GROUND-BASED ASTRONOMY FACILITIES

Ground-based optical/infrared astronomy has become an arena of intense international competition, especially in Europe and Japan. According to the decadal survey report (National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001), Europe and Japan have together invested in optical/infrared facilities at a level (relative to gross domestic product) greater than 10 times that of the NSF investment over a comparable period, and more than 3 times that of the combined federal, state, and private investment. The international optical/infrared capabilities are characterized by Japan's 8-meter Subaru Telescope, and the world's largest combined aperture: the European Southern Observatory's Very Large Telescope with four 8-meter telescopes in a single integrated complex. Europe, Japan, and Canada are partners with the United States in the Atacama Large Millimeter Array, which will consist of no less than 64 12-meter antennas in the Chilean high desert.

The soon-to-be-published *Astronomy and Astrophysics in the New Millennium: Panel Reports* (National Academy Press, Washington, D.C., 2001) contains much greater detail on the federal, international, and public/state observatories for radio, optical/infrared, and solar astronomy.

D

Glossary and Acronyms

Background radiation (cosmic)—The radiation left over from the Big Bang explosion at the beginning of the universe. As the universe expanded, the temperature of the fireball cooled to its present level of 2.7 degrees above absolute zero.

Brown Dwarf—A star-like object that contains less than about 0.08 the mass of the Sun and is thus too small to ignite nuclear fuels and become a normal star. Brown dwarfs emit small amounts of infrared radiation due to the slow release of gravitational energy.

Dark energy—An as yet unknown form of energy that pervades the universe. Its presence was inferred from the discovery that the expansion of the universe is accelerating, and these observations suggest that about 70 percent of the total density of matter plus energy is in this form. One explanation for dark energy is Einstein's cosmological constant.

Flat universe—Cosmological concept that states that the universe will expand forever at a decelerating rate, and will never pass an outer limit.

Gamma-ray bursts—A sudden burst of gamma rays coming from a source usually in deep space. The burst may last from a fraction of a second to several minutes.

Gravitational microlensing—Gravitational lensing due to a stellar mass object. This lensing phenomenon is termed "microlensing" because the mass of the lens is so small compared with that of a galaxy.

Microlensing of distant stars by intervening faint stars can reveal planets in orbit around the lensing star.

Interferometry—The main technique used by astronomers to map sources at high resolution and to measure their positions with high precision.

Kuiper Belt objects (KBOs)—Icy planetesimals distributed in a roughly circular disk in the outer regions of our solar system, 50 to 100 AU from the Sun.

Redshift—Radiation from an approaching object is shifted to higher frequencies (to the blue), while radiation from a receding object is shifted to lower frequencies (to the red). A similar effect raises the pitch of an ambulance siren as it approaches. The expansion of the universe makes objects recede so that the light from distant galaxies is redshifted. The redshift is often denoted by z, where $z = v/c$ and v is the velocity and c the speed of light.

AAPB	Astronomy and Astrophysics Planning Board
AASC	NRC Astronomy and Astrophysics Survey Committee
ACAST	Advisory Committee for AST (NSF Astronomical Sciences Division)
ACCORD	AURA Coordinating Council of Observatory Research Directors
ALMA	Atacama Large Millimeter Array
ARISE	Advanced Radio Interferometry between Space and Earth
AST	Advanced Solar Telescope (now called the Advanced Technology Solar Telescope, or ATST); NSF Astronomical Sciences Division
ATM	NSF Division of Atmospheric Sciences
AURA	Associated Universities for Research in Astronomy, Inc.
CAA	NRC Committee on Astronomy and Astrophysics
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CGRO	Compton Gamma-Ray Observatory
COMRAA	Committee on the Organization and Management of Research in Astronomy and Astrophysics
DOE	U.S. Department of Energy
EVLA	Expanded Very Large Array
EXIST	Energetic X-ray Imaging Survey Telescope
FASR	Frequency Agile Solar Radio telescope

GBT	Green Bank Telescope (now named after Senator Robert C. Byrd)
GLAST	Gamma-ray Large Area Space Telescope
GSMT	Giant Segmented Mirror Telescope
HENP	DOE Office of High Energy and Nuclear Physics
HEP	DOE Division of High Energy Physics
HEPAP	High Energy Physics Advisory Panel
HST	Hubble Space Telescope
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LSST	Large-aperture Synoptic Survey Telescope
MPS	NSF Mathematical and Physical Sciences Directorate
MPSAC	MPS Advisory Committee
MRE	NSF Major Research Equipment line
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRL	Naval Research Laboratory
NSAC	Nuclear Science Advisory Committee
NSF	National Science Foundation
NSO	National Solar Observatory
NVO	National Virtual Observatory
OMA	NSF Office of Multidisciplinary Affairs
OMB	Office of Management and Budget
OPP	NSF Office of Polar Programs
OSS	NASA Office of Space Science
OSTP	Office of Science and Technology Policy
ROTSE	Robotic Optical Transient Search Experiment
SAFIR	Single Aperture Far Infrared observatory
SAGENAP	Science Assessment Group for Experiments in Non-Accelerator Physics
SDO	Solar Dynamics Observatory
SKA	Square Kilometer Array
SPST	South Pole Submillimeter-wave Telescope

SSB	NRC Space Studies Board
SScAC	NASA Space Science Advisory Committee
TPF	Terrestrial Planet Finder
TSIP	NSF Telescope System Instrumentation Program
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Very Large Array