Federal Funding of Astronomical Research

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

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Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Preface

The Committee on Astronomy and Astrophysics (CAA), at its meeting on September 8, 1997, was briefed on the legislative report accompanying the bill to authorize appropriations for fiscal years 1998 and 1999 for the National Science Foundation (NSF). The report raised a number of questions about trends in support for research in astronomy and the overall robustness of the programs providing that support. At its meeting, the CAA heard the views of NSF and the National Aeronautics and Space Administration (NASA) on these issues. In consultation with the Board on Physics and Astronomy, the Space Studies Board, and representatives of NASA and NSF, the committee accepted the task of studying three of the questions raised by the House Science Committee (HSC). The three questions were framed by the CAA as follows:

1. What have been the trends in support for basic research in astronomy, as indicated, for example, by grant funding, growth in the number of astronomers, proposal success rate, average grant size and duration, acknowledgment of federal support in publications, and other measures of research vitality?
2. What are the current trends in federally funded support for basic research in astronomy, including support for theoretical astrophysics, and how is this support aligned with the availability of major observational facilities (including both ground- and space-based observatories)?
3. How vulnerable is the astronomical research community to unexpected setbacks, such as a catastrophic failure of the Hubble Space Telescope?

It was intended that the results of the study would help guide federal support of basic research for the next decade and serve as analytical input to the new 2000 decadal survey of the Astronomy and Astrophysics Survey Committee (AASC). The study would not offer specific funding recommendations, but rather would provide a background analysis of the alignment between available resources, agency priorities, and the vitality of the basic research program.

The HSC raised two additional sets of questions. The National Research Council (NRC) charged the Astronomy and Astrophysics Survey Committee (AASC) with addressing these questions:

1. Have NASA and NSF mission objectives resulted in a balanced, broad-based, robust science program for astronomy? Have the NASA and NSF missions been adequately coordinated, and has this resulted in an optimum science program from a productivity standpoint? What special strategies are needed for strategic cooperation between NASA and NSF? Should these be included in agency strategic plans?
2. How do NASA and NSF determine the relative priority of new technological opportunities (including new facilities) compared to providing long-term support for associated research grants and facility operation?

The task of responding to the HSC was divided in this fashion in order to avoid preempting the AASC's charge to set priorities for astronomy and astrophysics, to identify the main issues facing the field, and to make recommendations to address these issues. (Its recently released report, *Astronomy and Astrophysics in the New Millennium,* will be published in the fall of 2000.)

The CAA was careful to frame its own study as a data-gathering exercise intended to provide the objective basis for describing trends in the field, the primary value of which would be to support the work of the Panel on Astronomy Education and Policy of the AASC. For this reason, the CAA study articulates findings but does not recommend any actions to address the corresponding issues.

Notwithstanding the circumscribed nature of this CAA study on federal funding of astronomy, some striking facts came to light. These facts are outlined in the Executive Summary, and the data that support them are presented in the main body of the report.

The committee thanks Ron Konkel, who served as a consultant to the CAA and was very helpful in making clear what data were available and what questions might be addressed objectively. He was tireless in ferreting out the information needed by the committee in its study. The CAA would also like to thank Robert L. Riemer, Joel Parriott, and Kirsten Armstrong, who provided staff support and invaluable assistance in the review of the report and its publication.

John P. Huchra and Thomas A. Prince, *Co-chairs*

Committee on Astronomy and Astrophysics

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the 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 contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their participation in the review of this report:

Arthur D. Code, University of Wisconsin at Madison,
Frank D. Drake, University of California at Santa Cruz and the SETI Institute,
Richard S. Ellis, University of Cambridge, England,
Sandra M. Faber, University of California at Santa Cruz,
Richard M. Goody, Harvard University (retired),
Richard G. Kron, University of Chicago,
Marcia J. Rieke, University of Arizona,
Vera C. Rubin, Carnegie Institution of Washington, and
J. Anthony Tyson, Lucent Technologies.

Although the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

Contents

Executive Summary

As the result of a study to address questions about trends in and the current state of federal funding for the field of astronomy, the Committee on Astronomy and Astrophysics (CAA) developed the following four principal findings in response to the charge outlined in the Preface:

Finding 1. There has been a dramatic shift in the source of the funding for individual research grants in astronomy, with the National Science Foundation's (NSF's) share falling from 60 percent at the beginning of the 1980s to 30 percent at the end of the 1990s. The National Aeronautics and Space Administration's (NASA's) share of the grant funding has risen commensurately.

The continuing growth in funding for astronomy in the 1980s and 1990s has been largely the result of the success of NASA's space science program, in particular the launch of NASA's Great Observatories and several midsized facility-class satellites. Another important factor in the growth in funding for astronomy has been a large influx of private funding (from foundations and universities) for the construction of ground-based telescopes.

Finding 2. The overall level of federal support for astronomy remains strong, but shifts in funding patterns, with NSF supplying a declining percentage of grant funding relative to NASA, have the potential to create imbalances that could be detrimental to the overall health of the field. For example, funding for broad-based astrophysical theory has not kept pace with the growth in funding for astronomical research overall.

With NSF's relative role in astronomy continuing to shrink, the subfields that depend primarily on NSF funding are vulnerable. Over the past 15 years, there has been essentially no significant change in the annual budget of NSF's Division of Astronomical Sciences. As a consequence, the fraction of support for the U.S. astronomy enterprise provided by NSF has declined. This trend substantially affects the grants programs, since the number of astronomers has increased over the same 15-year period by more than 40 percent. Increases in NASA funding have taken up the shortfall in some areas such as optical and infrared astronomy; however, an increasing emphasis on mission-oriented support has created vulnerabilities in those subfields for which NASA support is not readily available, such as broad-based theory, computational astrophysics, and radio astronomy, where some erosion in grant funding already is evident. The committee was unable to produce an exhaustive list of vulnerable research areas but suggests that funding balance across subfields of astronomy is an important issue that requires further study.

Finding 3. Although the number, size, and capability of ground-based observing facilities, both public and private, have increased considerably, there has been no commensurate increase in NSF funds for utilizing these facilities (i.e., for instrumentation, individual research grants, or theory).

Rapid growth and change create problems of adjustment. Funding for utilization of both ground-and space-based astronomical facilities remains an important issue. There are some fields of astronomy in which support has not been adequate to exploit the dramatic scientific discoveries of the last decade or to pursue the opportunities offered by the explosion in scientific capabilities. For instance, ground-based facilities have grown in number and scope with the completed, or soon to be built, large, private- and state-funded ground-based telescopes and with NSF initiatives that include the Green Bank Telescope, the Gemini telescopes, the Arecibo telescope upgrade, and the Atacama Large Millimeter Array (ALMA/MMA). Yet funding for instrumentation, theory, and observer grants at NSF has not kept pace with support for construction. Facility instrumentation for major new telescopes is a clear need for the foreseeable future in response to the leaps in technical capabilities and the large increase in telescope collecting area. Training of instrumentalists for both ground- and space-based facilities is also an outstanding need.

Finding 4. As a result of NASA's increased role in astronomical research funding, a large portion of the total support is tied to a few flagship space missions.

NASA is a mission agency whose program is strongly focused on initiating and launching space-based instruments. Funding for operations and research accompanies each mission. This paradigm has been extremely effective in maximizing the scientific return from these missions. However, the worrisome corollary of this arrangement is the potential for premature termination of the research support associated with a mission in the event of a catastrophic mission failure. Although NASA has a strategic planning process that is quite effective in engineering smooth transitions from one mission to another, there appears to be little explicit planning for unexpected or premature mission termination.

If a centerpiece astronomical research mission in space were to fail at a time when follow-on missions were far in the future, the impacts would include not only the loss of a major observational tool, but also the premature termination of the stream of research data and the flow of funds to analyze the data. Because analyzing the data from such major missions is the work of a significant fraction of the astronomy and astrophysics research community, the personnel impact could be substantial, which could in turn dampen the community's ability to help plan for, and utilize, future missions. For example, the Hubble Space Telescope (HST) grants program accounts for roughly 25 percent of all individual investigator funding in astronomy. It supports researchers at all levels, including students and postdoctoral fellows. In the event of an HST failure, the additional loss of jobs directly associated with the Space Telescope Science Institute and NASA's Goddard Space Flight Center would be substantial, not to mention the loss of a primary scientific capability. Recovery of the scientific personnel complement and the nation's astronomical research capability from such a catastrophe would be slow.

Most important is that a significant fraction of the support for the youngest members of the field comes from such missions. The impact on the youngest astronomers, such as those supported by Compton Gamma Ray Observatory, Hubble, and Chandra fellowships and those supported by the research and analysis (R&A) funds for such missions, would be disproportionately large and would significantly affect the future of the field.

The committee's four findings have led it to suggest that the following proposition be considered in future assessments of the field: plans for future facility construction, both ground and space based, should be accompanied by a strategy to accomplish the scientific mission, including provision of instrumentation for ground-based telescopes, support for observations, and funds for the necessary and relevant astrophysical theory. The strategy should address the following objectives:

- Ensuring continuity of research in critical subfields in the event that major facilities are lost or significantly delayed;
- Developing new instrumentation for both space- and ground-based facilities;
- Training instrumentalists;
- Optimizing the distribution of spending on hardware and personnel; and
- Maintaining flexibility to respond to changes in the directions of research in astronomy and astrophysics.

In conclusion, the committee found the field of astronomy in the United States to be in generally good health. The United States still leads the field. New discoveries continue to be made at a quickening pace. Observational capability continues to grow rapidly with the construction and deployment of ground- and space-based instruments of remarkable power. There is strong public interest in astronomy. However, the dramatic shift in the majority of research grant support from NSF to NASA over the past two decades has led to a system in which the funding for subfields that cannot rely on NASA support has eroded somewhat and the funding for the field as a whole is vulnerable to the unexpected termination of a major NASA mission.

1

Introduction

The 1991 National Research Council (NRC) report *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington, D.C., 1991; hereinafter referred to simply as the 1991 Decadal Report) noted that the National Aeronautics and Space Administration (NASA) was becoming the dominant agency in astronomy research grant funding. In 1982, the National Science Foundation (NSF) provided about 60 percent of the federal support for individual grants. By the end of the decade, NASA was providing more money for individual astronomy research grants than NSF, a trend that continued into the 1990s with the guest observer programs for the Hubble Space Telescope, Compton Gamma Ray Observatory, ROSAT (Germany's Röentgen Satellite), and other NASA missions. NSF funding has remained relatively flat in real dollars, despite the pressures of new facilities, growth in both the astronomical community and public interest in astronomy, and the opening of new astronomical frontiers.

This change in the basic way astronomical research is funded, as well as changing demographics, may profoundly affect the way astronomy is carried out today. NASA is generally a mission-oriented agency, whereas NSF's primary goal is to fund basic research. Despite NASA's mission orientation, the support for observations and related theory on both ground-based and satellite observatories under NASA sponsorship is primarily science driven and parallels (and now exceeds) NSF's funding of basic research in astronomy. Science also progresses at different rates in different areas as technology changes, key new discoveries are made, and new areas of research open up.

As we enter the 21st century, there is concern that the way in which astronomical research is now funded may negatively affect the health of the field. In particular, concerns have been raised that some crucial subfields of astronomy are being underfunded. In parallel, there has been significant growth in ground-based facilities but a lack of growth in instrumentation and operations funding, which leads to the concern that, without better support for new facilities, the United States may lose its commanding leadership position in astronomy and astrophysics. In connection with the effort reflected in the recently released 2000 decadal survey, [1] it is important to understand how the field of astronomy has changed in the past decade as a result of changes in the sources of funding and the availability of new, large telescopes.

This report was commissioned by NSF and NASA, as directed in the fiscal year (FY) 1997 House Authorization report language, to present available information on the three key questions stated in the Preface and summarized as follows:

1. What have been the trends in support for basic research in astronomy?
2. Has basic research support kept pace with the development of new facilities in NASA and NSF, and is the balance of support across subdisciplines appropriate?
3. Is the field or any major subfield vulnerable to a catastrophic failure, such as the loss of the Hubble Space Telescope (HST)?

[1] National Research Council, *Astronomy and Astrophysics in the New Millennium,* National Academy Press, Washington, D.C., 2000, forthcoming.

In this report, the Committee on Astronomy and Astrophysics (CAA) examines the trends in grant funding, number of proposals received, number funded, average grant size, publication rates, and other measures of the health of basic research in astronomy. It compares these trends to information on field demographics, such as the number of astronomers and the fraction of active research astronomers working in several fields and disciplines. Its objective is not to evaluate the appropriateness of the overall funding level for astronomy, but rather to assess the balance of current funding and identify any vulnerabilities that may affect the future health of the field. The committee draws some basic conclusions about research support and examines the effects that the failure of HST or another major space mission would have on the field. Recommendations and priorities for federal funding of astronomy are presented in the 2000 decadal survey prepared by the Astronomy and Astrophysics Survey Committee (AASC).

In the process of preparing this report, the committee gathered data on the research budgets of several federal agencies and learned a great deal about how the data are recorded and reported. Although it is only peripheral to the committee's primary charge, this report discusses means to improve the tracking of astronomy research expenditures at NSF and NASA.

To provide a context and perspective for interpreting the findings of this report, Chapter 2 begins with an update of the funding trends discussed in the 1991 Decadal Report. Chapter 3 discusses the process and methodology of the study. Chapter 4 addresses the question of changing demographics in the field. Chapter 5 provides a more detailed discussion of the major sources of funding for astronomy. In Chapter 6 the committee summarizes and discusses implications of the results of its study and in Chapter 7 presents its principal findings.

Two sets of questions from the FY 1998 House Authorization bill that were included in the charge to the AASC are not addressed in this report:

1. Have NASA and NSF mission objectives resulted in a balanced, broad-based, robust science program for astronomy? NASA's mission is to fund research that supports flight programs and campaigns such as Origins, whereas NSF's mission is to support basic research. Have these overall missions been adequately coordinated, and has this resulted in an optimum science program from the standpoint of productivity? The Panel on Astronomy Education and Policy should ensure that agency strategic plans or other plans developed in response to the Government Performance and Results Act (GPRA) adequately address these needs.
2. How do NASA and NSF determine the relative priority of new technological opportunities (including new facilities) compared to providing long-term support for associated research grants and facility operations?

2

Back to the Past: An Update on the 1991 Decadal Report

The 1991 Decadal Report contained a compendium on the demographics of astronomy. In this chapter the CAA recalls that information with the aim of providing a quick overview and a historical perspective on the key indicators of the health and status of the field of astronomy.

For convenience, the committee's findings are presented in an order that parallels that of the 1991 Decadal Report.

2.1 THE DEMOGRAPHICS OF ASTRONOMY

The 1991 Decadal Report charted the growth in the number of astronomers from 1981 to 1989, an exercise that showed the field had grown by 42 percent during the decade of the 1980s. What has happened since 1989? Figure 2.1 shows the total, full, and junior membership of the American Astronomical Society (AAS) from 1984 to 1999. AAS full members represent active professionals in the field; about 18 percent of the AAS full members are at foreign institutions. The growth of the field has slowed since the last decade, and the growth in the number of active researchers—as measured by full members of the AAS—has slowed as well. However, the astronomical community is still growing significantly faster than the U.S. population as a whole. The demographics of the astronomical community are discussed further in Chapter 4.

The 1991 Decadal Report also commented on the percentages of women and minorities in the field. Women made up 8, 12, 13, and 16 percent of the astronomical community in 1973, 1987, 1990, and 1995, respectively, as measured by the fraction of AAS membership. This trend has followed increasing enrollment by women in graduate programs as tracked by the American Institute of Physics (AIP).

According to AAS information, the median age of astronomers in 1995 was about 41 for men and 34 for women. For all astronomers, the median age was about 40. There is no evidence of the “graying” of astronomy. However, there has been a major change in the age distribution of the field. Whereas in 1987 half of all astronomers were between the ages of 35 and 50, in 1995 the distribution of ages was somewhat broader, with about 40 percent of astronomers in the same age range.

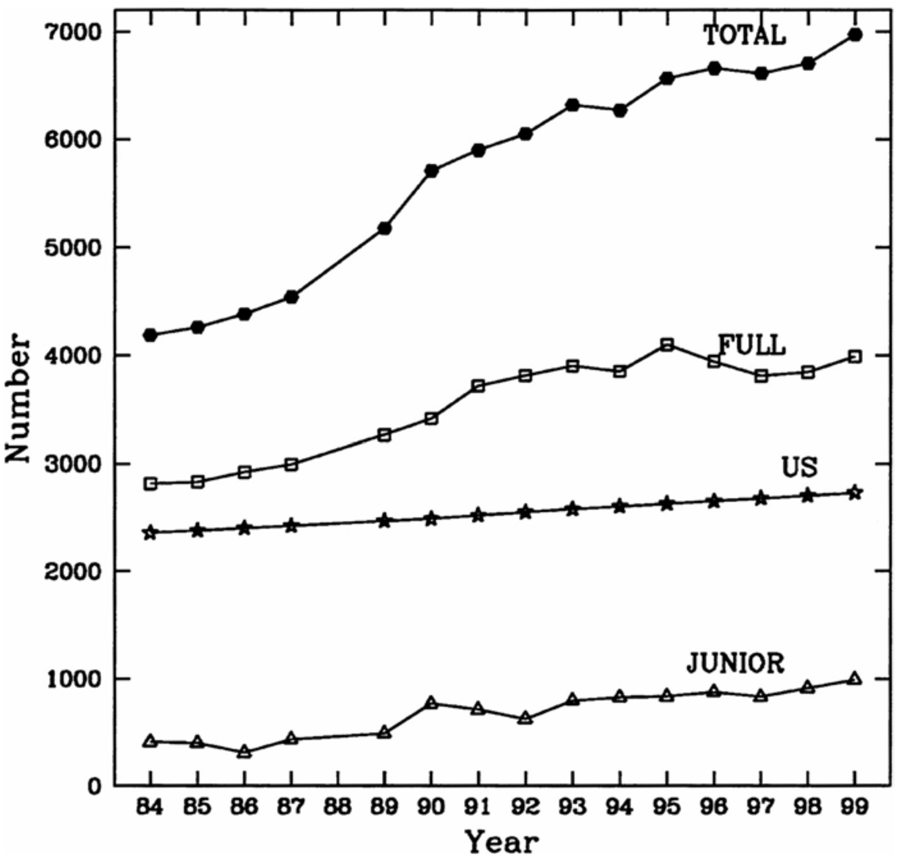

FIGURE 2.1 Growth in the number of U.S. astronomers as represented by membership in the American Astronomical Society. For comparison, growth in the U.S. population (scaled by 1/100,000) is plotted for the same period. SOURCE: Data are from the AAS (*Bulletin of the American Astronomical Society,* 1984-1999) and the Population Estimates Program, Population Division, U.S. Census Bureau.

2.2 THE FUNDING OF ASTRONOMY

At the time of the 1991 Decadal Report, the status of funding was reasonably clear: NSF provided the major share of funding for ground-based astronomy; NASA provided most of the funding for space astronomy; a significant component was provided by state and private funding (estimated at $190 million per year); and some support for special projects came from the Department of Energy, Department of Defense, and Smithsonian Institution. In 1989, in the *Astrophysical Journal* (ApJ), 34 percent of the articles acknowledged NSF funding, 39 percent acknowledged NASA funding, and 10 percent acknowledged other forms of federal funding. Has the balance of federal funding changed significantly? The committee found that in the 1995 ApJ, 42 percent of the papers published acknowledged NASA support, but only 24 percent acknowledged NSF.

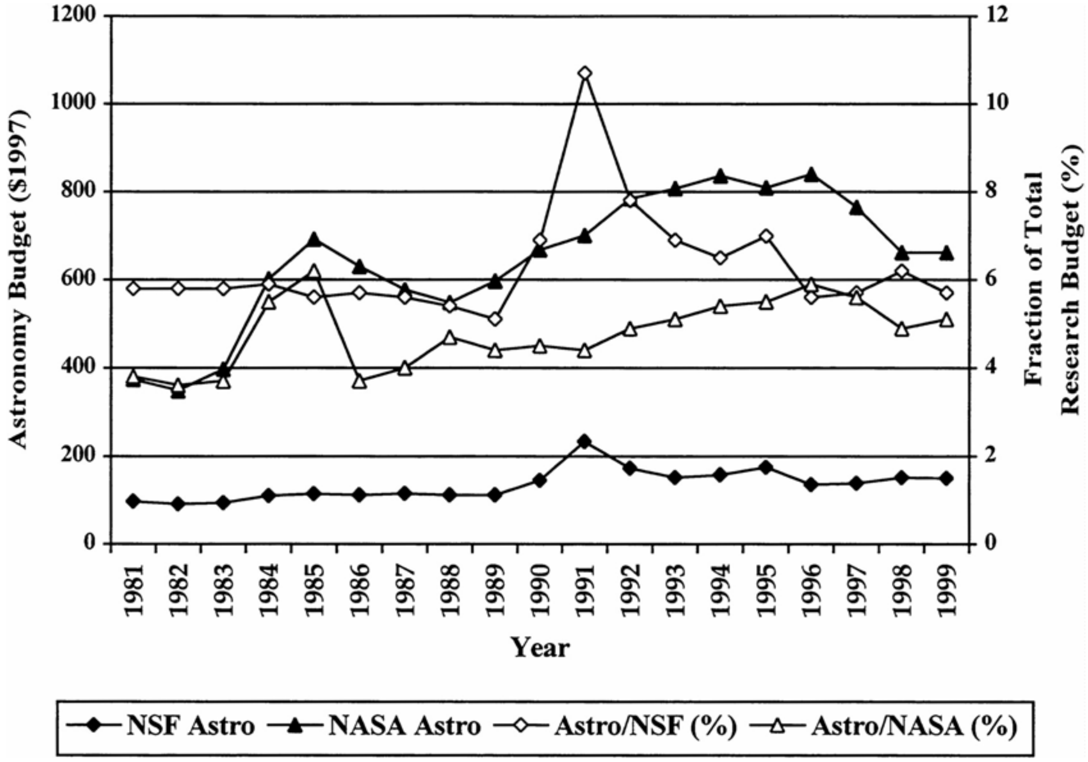

FIGURE 2.2 Overall funding of astronomy by NASA and NSF. Astro/NSF and Astro/NASA are the relative fractions of the NSF and NASA research and development budgets allocated to astronomy and astrophysics research (right-hand scale). SOURCES: 1991 Decadal Report (1981-1985), NSF and NASA (1986-1999).

Figure 2.2, an updated version of Figure B.2 of the 1991 Decadal Report, shows the overall funding of astronomy by NSF and NASA and the fraction of the agency budgets allocated to astronomical research. It makes clear that NASA dominates the total funding for astronomical research, as it has since at least 1981. This is due, of course, to the large amount of NASA funding going into space astronomy projects such as the HST; the Advanced X-ray Astronomy Facility (AXAF), now called the Chandra X-ray Observatory (hereinafter Chandra); and the Space Infrared Telescope Facility (SIRTF).

More interesting from the perspective of the current study is whether there has been a shift in the grant funding to individual researchers from NSF to NASA. Figure 2.3, Figure 2.4 through Figure 2.5 update the information presented in the 1991 Decadal Report.

2.2.1 Support from NSF

The 1991 Decadal Report documented a steady decline in the fraction of the total NSF research budget allocated to astronomy, from a historical level of more than 6 percent to about 5 percent by the end of the decade. A similar trend occurred in the 1990s. As Figure 2.2 indicates, the fraction of NSF funding going to astronomical research at the end of the decade was a little more than 5 percent of the NSF R&D budget. However, between 1990 and 1995, the funding level was higher, typically 7 to 8 percent of the budget, with an increase to almost 11 percent in 1991 due to the one-time increment in funding for the construction of the Green Bank Telescope (GBT).

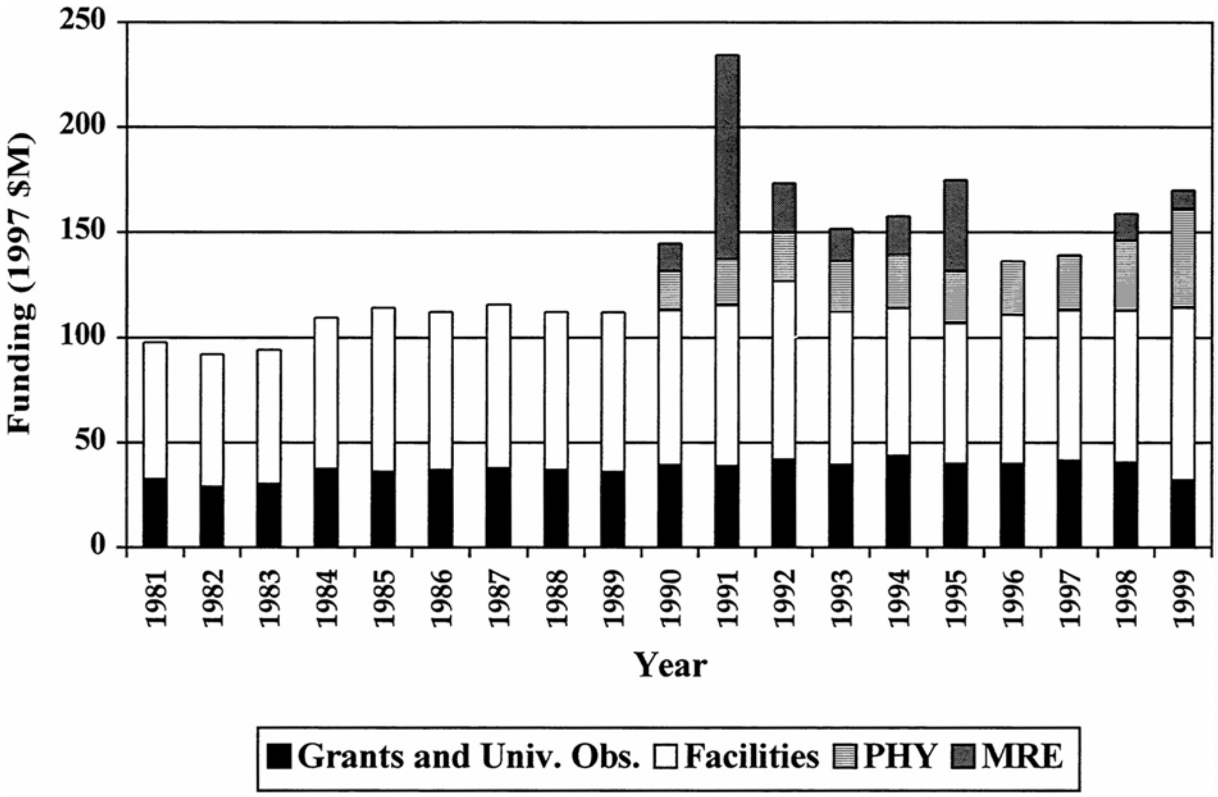

FIGURE 2.3 NSF funding for astronomy. Note that funding for university observatories is grouped with that for grants, as in the 1991 Decadal Report. NOTE: Major research equipment (MRE) bars include funding for the Green Bank Telescope in 1991. The funding denoted by PHY includes support for astrophysics 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 has not been included in either the MRE or the PHY category in this figure. SOURCE: 1991 Decadal Report (1981-1985), NSF (1986-1999).

Figure 2.3, an updated version of Figure B.3 in the 1991 Decadal Report, indicates where the increases come from. Funding for major research equipment (MRE) provided large increments in funding from 1990 to 1995. The MRE funding includes VLBA ($35 million between 1990 and 1993), Gemini ($95 million between 1991 and 1995), and the GBT ($81 million in 1991). All funding levels are given in FY 1997 dollars. Also shown in Figure 2.3 is the funding for astronomy and astrophysics from NSF's Physics Division. This includes funding for theory, atomic and molecular astrophysics-related research, and submillimeter and IR astronomy from the South Pole. Further details are given in Chapter 5. Funding levels for astrophysics programs from the Physics Division were not included in the 1982 Decadal Report (National Research Council, *Astronomy and Astrophysics for the 1980's,* National Academy Press, Washington, D.C., 1982). Inclusion of these programs would have resulted in astronomy and astrophysics support that was higher than that shown in Figure 2.2 and Figure 2.3. However, Figure 2.3 shows that the core funding of astronomy grants and facilities operation from NSF's Division of Astronomical Sciences has been relatively flat in constant FY 1997 dollars between 1990 and 1999. During the same period, the total NSF R&D budget rose by 26 percent.

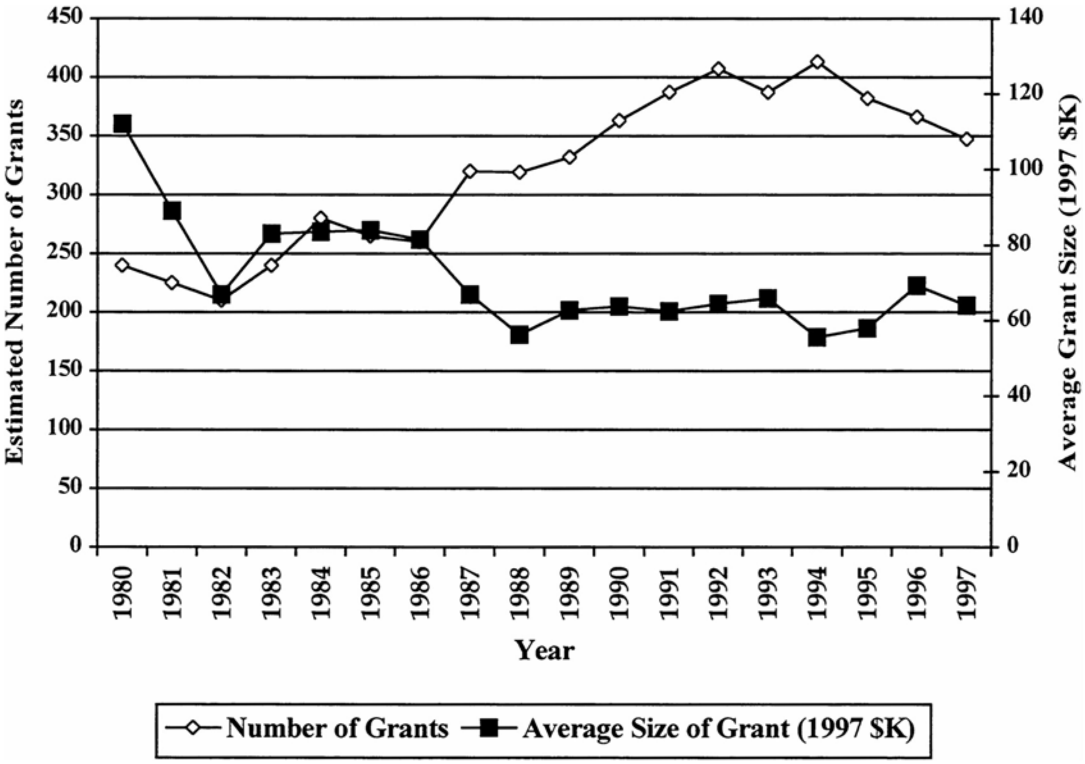

FIGURE 2.4 NSF astronomy research grants program. Filled squares show the average grant size (right-hand scale), which has been decreasing in 1997 dollars. Open diamonds show the number of grants funded annually, which has risen. (See Section 5.1.4 for further analysis of the NSF grants program.) SOURCE: 1991 Decadal Report (1981-1987), NSF (1988-1997).

Figure 2.4 is an update of Figure B.4 of the 1991 Decadal Report and provides a more detailed view of the trends in grant funding. The 1991 Decadal Report documented the disturbing trend of a decrease (by 50 percent) in the average NSF grant size. Since 1990, the average grant size appears to have stabilized. The 1991 Decadal Report made the further observation that the size of the average grant had dropped below the critical size required for support of a faculty summer salary plus a graduate student and travel. The consequence was that scientists often had to seek support from multiple grants, with a resultant increase in overhead for preparing, reviewing, and managing a larger number of smaller proposals. In the 1990s, astronomers appeared to turn increasingly toward NASA as a new source of funding to offset the dwindling size of NSF research grants.

2.2.2 Support from NASA

The 1991 Decadal Report stated clearly, “NASA is becoming the dominant agency in astronomy grant funding. In 1982, NSF provided about 60 percent of the federal support for individual grants” (p. 156). However, by the end of the 1980s, NASA had provided more grant money than had NSF, and the 1991 Decadal Report stated that “in the 1990s, NASA's grant support for data analysis is expected to increase even more.” This prediction was indeed correct. From 1989 to 1999, NASA's grant funding for astronomy increased by about a factor of two in constant dollars. During the same time, grant and university observatory support from NSF remained flat; thus, the fraction of research grant funding supported by NSF continued to decrease during the 1990s. In a span of about 15 years, support for the field of astronomy made a major (and largely unplanned) transition from one federal agency to another.

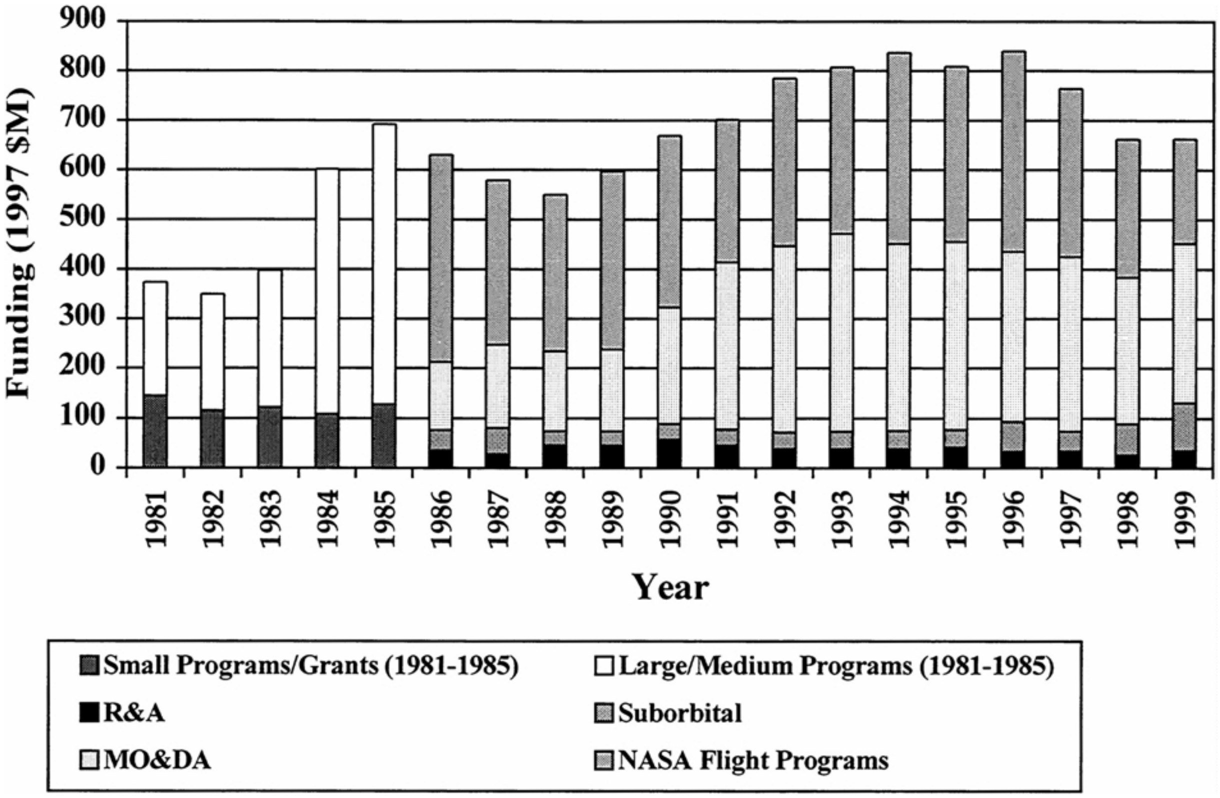

FIGURE 2.5 NASA astronomy budget. SOURCE: 1991 Decadal Report, NASA, and the Congressional Record.

Figure 2.5 details the portion of NASA funding going to various components of the astronomy program. For 1981 to 1985, the data are taken from the 1991 Decadal Report and show the breakdown of astronomy funding into two components: (1) large and medium missions and (2) small programs and grants. For the period beginning in 1986, more detailed and uniform information is available. The large-and medium-mission component is roughly replaced by two components: (1) flight programs and (2) mission operations and data analysis (MO&DA). The small programs and grants component is roughly replaced by two other components: (1) the research and analysis (R&A) program and (2) the suborbital program (primarily support for SOFIA). In both cases, the replacement is approximate, primarily because MO&DA includes support of programs that would fall under the category of small projects and grants in the classification used in the 2000 decadal survey. Note that the increase in MO&DA funding in 1990 is due to the HST program.

2.2.3 Trends in Astronomical Research

Lastly, it is important to point out some real and perceived changes in astronomical research. Three major changes are (1) the increase in international projects both in space (see the NRC report *U.S.-European Collaboration in Space Science,* National Academy Press, Washington, D.C., 1998) and on the ground (Gemini, ALMA); (2) the increase in university-based consortia to build and operate midsized-to-large telescopes (Keck/California Association for Research in Astronomy [CARA]; Astronomical Research Corporation [ARC]; Berkeley-Illinois-Maryland Array [BIMA]; Wisconsin, Indiana, Yale, and NOAO [WIYN]; MDM Observatory [consortium of University of Michigan, Dartmouth College, Ohio State University, and Columbia University]; Southern Observatory for Astronomical Research [SOAR], etc.); and (3) the general increase in the size of research groups pursuing large and long-term programs. Examples of large astronomical scientific programs are the Sloan Digital Sky Survey (SDSS), the HST Key Projects on quasar absorption lines and the extragalactic distance scale, and the Two-Micron All-Sky Survey (2MASS).

Telescope consortia have generally increased preferential access to the community; as indicated below, the fraction of observational optical and infrared astronomers at institutions without moderate to large telescopes has dropped over the decade from about 58 to about 48 percent. As the field matures, many of the remaining scientific problems are of a scale and complexity that they can be approached only by large groups of researchers with varied expertise. These trends all reflect the natural evolution of the field.

To the great benefit of the community, much of the program outlined in the 1991 Decadal Report has been realized. With international collaborators, the 8-meter Gemini telescopes are nearing completion. Both SIRTF and the Millimeter Array (now ALMA) appear to be on track, although the new start for SIRTF was later than originally hoped for and ALMA construction still has to be approved by the National Science Board (NSB). The Far Ultraviolet Spectroscopic Explorer (FUSE) has been launched, the Stratospheric Observatory for Infrared Astronomy (SOFIA) is on track, and there has been significant progress in adaptive optics and laser guide stars. There are now working prototype optical-infrared interferometers, two shared 4-meter telescopes (ARC and WIYN) have been constructed, and one more (SOAR) is on the way. For the ground-based optical and infrared (OIR) community, (see the NRC report *A Strategy for Ground-Based Optical and Infrared Astronomy,* National Academy Press, Washington, D.C., 1995), several new 8-meter-class telescopes have been constructed or are well under way.

New fields of astronomy have opened up. The Hubble Space Telescope has transformed the way observational optical and near-ultraviolet astronomy is done, not only with the tremendous improvements attributable to getting above Earth's atmosphere but also with its Guest Investigator program. The Hubble Deep Fields have given researchers their best look yet at the early universe and whet our appetite for the additional data and theory necessary to understand the formation of galaxies and the first objects in the universe. The data are beginning to become available as large ground-based telescopes reveal an increasing number of galaxies with ages 90 percent of the way back to the beginning of the universe, and submillimeter instruments such as SCUBA are revealing a new component of dust-enshrouded galaxies at high redshift. The Cosmic Background Explorer (COBE) clearly observed fluctuations in the microwave background and, in doing so, has strongly confirmed the Hot Big Bang model. The BOOMERANG (Balloon Observatories of Millimetric Extragalactic Radiation and Geophysics) balloon experiment has resolved the fluctuations and has shown that we live in a “flat” universe. The newly launched Chandra X-ray Observatory is beginning to probe the synthesis of elements in supernovae and is uncovering new populations of active galaxies at high redshift. The combination of the Compton Gamma Ray Observatory (CGRO), BeppoSax, Keck, HST, the VLA, and other ground-based telescope observations has shown that gamma-ray bursts are powerful explosions at cosmological distances. However, the source of these explosions remains uncertain.

A new generation of ground-based high-energy and neutrino telescopes has come on line (Milagro, Super Kamiokande, Antarctic Muon and Neutrino Detector Array [AMANDA], Sudbury Neutrino Observatory [SNO], Fly's Eye, etc.), significantly improving the ability to understand energetic astrophysics, but also bringing forth new puzzles. Studies of binary pulsars have provided exquisite tests of general relativity, and more are yet to come with NASA's Gravity Probe B, the NASA Laser Interferometer Space Antenna (LISA) mission, and NSF's Laser Interferometer Gravitational-wave

Observatory (LIGO). Extrasolar planets have been discovered, but not necessarily where they were expected to be in their stellar systems. Protoplanetary disks have been found around many young stars. What is the nature of the "dark matter" and "dark energy," if any really exists? A complete theory of star formation still eludes our grasp and, with it, both a complete theory of galaxy formation and a complete theory for the formation of large-scale structures in the universe, although significant strides have been made in showing that gravitational instability is the dominant process.

3

Process and Methodology of This Study

3.1 KEY QUESTIONS

In carrying out this study of federal funding for astronomy, the committee began by attempting to answer the following key questions:

- What is the current structure of facilities, institutions, and human resources engaged in astronomical research in the United States?
- How has this structure changed over the past decade?
- What is the federal agency role in the funding and maintenance of the U.S. astronomy infrastructure?
- How are the major federal agencies involved? Is this changing over time?
- What is the balance among the agencies, facilities, and institutions engaged in astronomical research?
- Are the arrangements for funding research resilient and efficient from a public policy perspective?
- How is theoretical research in astronomy funded?
- Are the demographic and educational characteristics of the astronomy community appropriate to ensure the continuing scientific vitality of the profession?
- What is the balance between established researchers and newly trained scientists?
- How are astronomers and astrophysicists distributed among the various subfields of astronomy?

The committee had various degrees of success in answering these questions. In general, broad questions such as the funding balance between NSF and NASA and the funding balance between facilities and human resources were the easiest to quantify with existing data.

3.2 TYPES OF DATA GATHERED

The committee gathered data reflecting both a top-down and a bottom-up perspective. The top-down perspective gives an overall view of the balance of funding between agencies and a rough view of the division of funding between facilities and human resources. The bottom-up perspective provides information on the demographics of the field, including the relative numbers of astronomers and astrophysicists in various subfields, funding for activities in the subfields, and patterns of publication in these subfields.

Among the types of data gathered were the following:

- Agency budget documents;
- Professional membership rosters, primarily of the American Astronomical Society and the Astrophysics Division of the American Physical Society (APS); and
- Academic degree and enrollment statistics.

Specific data sources included the following:

- Federal agency personnel;
- Federal procurement awards databases;
- AAS and APS astrophysics membership lists;
- Agency and association Web sites;
- NSF Division of Science Resources Studies (SRS) data resources and reports; and
- The *Astrophysical Journal, Astronomical Journal, Monthly Notices of the Royal Astronomical Society, Physical Review, Icarus, Nature, Science, Publications of the Astronomical Society of the Pacific,* and NASA's Astrophysical Data System.

3.3 LIMITATIONS OF DATA RESOURCES

Although numerous data are available that relate to the federal funding of astronomical research, there are limitations, which in some cases are severe, on the uniformity and completeness of the data set. For instance, at both NSF and NASA, the readily available budget and procurement records often do not specifically itemize astronomical research. As a consequence, the fraction of funding going to astronomical research must sometimes be estimated as a fraction of a larger budget.

In many cases, the data on funding for a given type of astronomical research are often spread unevenly across multiple agencies and institutions. Particular examples are theory and instrumentation, subareas of astronomical research that are funded from many different sources within NASA, NSF, the Department of Energy (DOE), and private institutions.

Although these limitations make it impossible to carry out a complete and detailed audit of astronomy research funding over the past 20 years, they did not prevent the committee from carrying out the objectives of this study. This was accomplished by compiling accurate year-by-year statistics on the major research expenditures in astronomy, combined with “snapshots” of selected fiscal years to provide a more detailed picture of funding patterns and their evolution over the past decade. When relevant, the committee provides clear explanations of what data are presented, their source, and the assumptions made in presenting the findings.

4

Demographics

Demographic information for the field of astronomy is critical to addressing several of the key questions posed in Section 3.1. In particular, demographic trends such as the number of astronomers are important in determining the stability and availability of funding over time. As much as possible, demographics should be gathered for individual subfields to ascertain whether or not there have been dramatic shifts in the number of astronomers working in a given subdiscipline and whether or not such shifts correlate with comparable changes in funding between subdisciplines.

The committee gathered several types of demographic data: AAS membership and full membership records, graduate enrollments and Ph.D. production, and publication statistics from the literature, including citations of funding sources. The committee also obtained the APS Division of Astrophysics membership list for 1998.

Other useful demographic information would be the distribution of astronomers and astrophysicists by type of employment (e.g., postdoctoral scientist, staff scientist, or professor) and by tenure status. Such demographic information was not gathered for this particular study but is being gathered by the AAS.

4.1 NUMBER OF ASTRONOMERS

The total number of astronomers, as measured by AAS membership and AAS full membership, continued to increase through this decade (see Figure 2.1), but the number of active researchers, as measured by AAS full membership, has leveled off over the past five years. The number of junior members also continued to increase, and this increase is consistent with the continued increase in the number of degree recipients and graduate enrollments shown in Figure 4.1.

(Note that the total number of U.S. astronomers is best estimated by combining the AAS and APS Division of Astrophysics rolls. In 1998 there were approximately 6,700 AAS members, of which 18 percent were foreign (as determined by address, not citizenship), for a total of approximately 5,500 U.S. resident AAS members. In 1998 there were approximately 1,600 members of the APS Division of Astrophysics, of which approximately 9 percent were at foreign addresses. Of the approximately 1,450 U.S. members, about one-third are also members of the AAS. Thus, the combined number of U.S. AAS members and non-AAS, APS Division of Astrophysics members was approximately 6,500 in 1998. This represents a lower limit, since there are professional astronomers who are not members of either society.)

Astronomy graduate enrollment has declined approximately 10 percent since its peak a few years ago (Figure 4.2). However, this decline is smaller than that for graduate physics enrollment, which has dropped by approximately 20 percent since its peak (*Enrollments and Degrees Report*). Astronomy Ph.D. production, including physics department students doing astronomical and astrophysical dissertations, continued to rise in the last three years, in contrast to Ph.D. production in physics and the physical sciences in general. (It is important to note from these data that the theses of approximately 5 to 7 percent of physics students are in astrophysics. This is why astronomy enrollments represent only 7 percent of physics, even though 13 percent of the combined physics and astronomy Ph.D.s produced are in astronomy and astrophysics.) Astronomy remains arguably the most vibrant of the physical sciences in the United States.

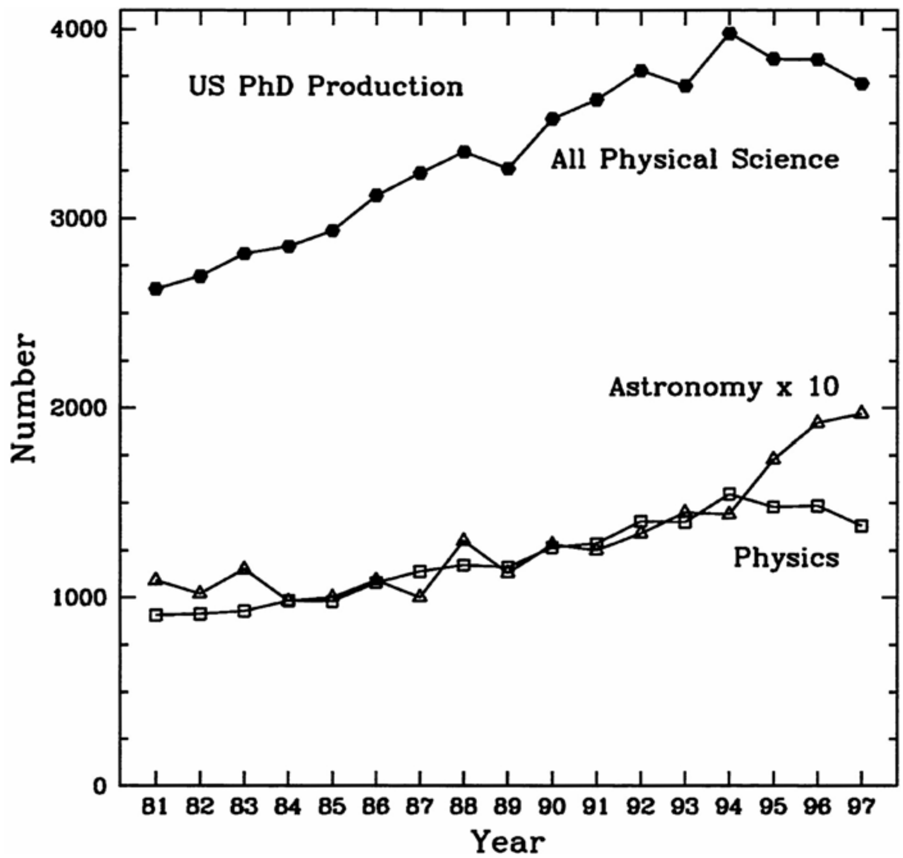

FIGURE 4.1 Astronomy Ph.D. production, 1981-1997, compared to Ph.D. production for all physical sciences and for physics alone. SOURCE: NRC, Office of Scientific and Engineering Personnel (OSEP), *Summary Report 1996 Doctorate Recipients from United States Universities,* National Academy Press, Washington, D.C., 1998; unpublished data from OSEP.

To gain further insight into the trends in the number of astronomers, the committee estimated the fraction of astronomers by discipline (typically by wavelength orientation) and also by scientific field (e.g., planet formation, stellar astronomy, instrumentation) from the AAS membership lists. This was done for two years, 1989 and 1997, before and after the 1991 Decadal Survey. In both cases, random samples of 600 to 700 full, U.S. members were drawn from the AAS rolls. U.S. AAS membership refers to residency in the United States and its territories and commonwealths (e.g., Guam, Puerto Rico).

Individuals were classified by discipline, field, and place of employment. The classifications employ a fairly simple mnemonic: OO - observational optical, OR - observational radio, and so forth. The full lists of classification categories are given in Table A.1 in Appendix A. These same categorizations were used for the classification of publications and funding sources discussed below in Section 4.2. The committee is aware that many individuals fall into more than one of the categorizations and that because only about 20 percent of the U.S. full AAS membership was sampled, the accuracy of the estimates for distribution by discipline and field is necessarily limited. Nonetheless, such categorizations are useful.

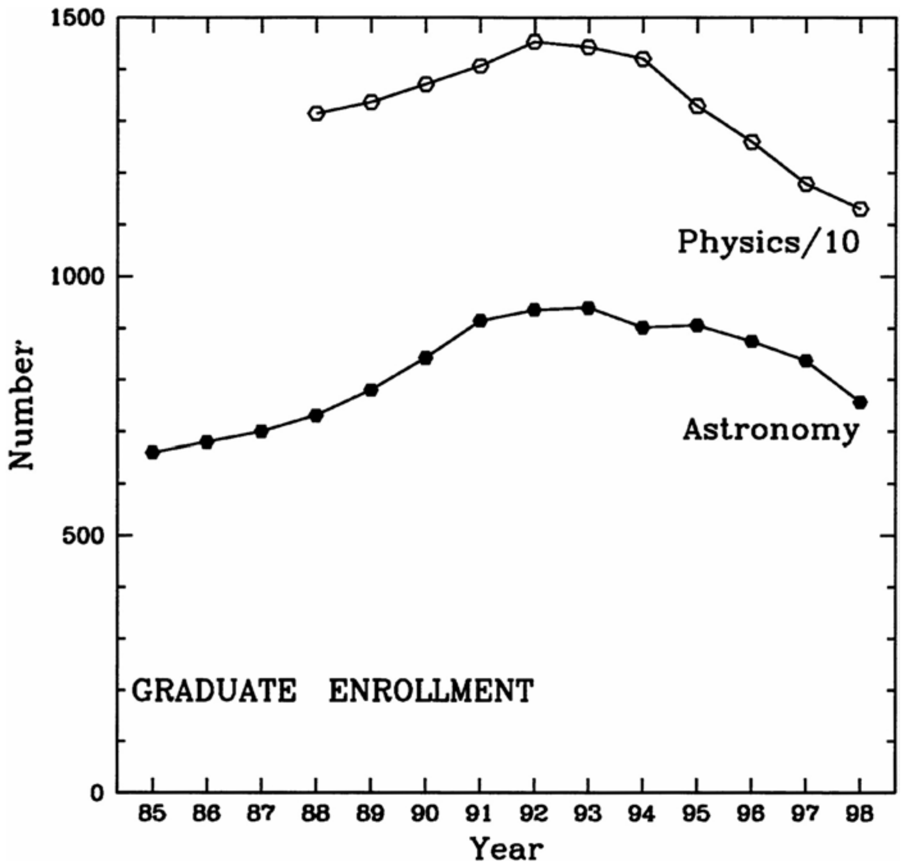

FIGURE 4.2 Astronomy and physics graduate enrollment, 1985-1998. Note that enrollment in physics is approximately 15 times that in astronomy. SOURCE: Data from Patrick J. Mulvey and Starr Nicholson, *Enrollments and Degrees Report,* American Institute of Physics, College Park, Maryland, 2000, see <http://www.aip.org/statistics/trends/undtrends.htm > ; *The American Astronomical Society's Examination of Graduate Education in Astronomy,* available online at <http://www.aas.org/publications/baas/v29n5/edrpt.html>.

Field and discipline classifications were based primarily on literature searches in NASA's Astrophysical Data System (ADS) and indexes of the main journals. This information allowed fairly accurate classification of 85 to 90 percent of the sample. Place of employment was determined from the address in the AAS directory or, if only a home address was given, from the institutional affiliation given on papers published in or near the year surveyed. In what follows, people who could not be assigned fields or disciplines (NA in Table A.1) are not counted in computing fractions of the community. Despite maintaining AAS full membership, they probably were (1989) or are (1997) no longer active researchers publishing work in the field of astronomy. For those cases in which the committee could determine that individuals were *not* employed in any of the major categories, they were counted in the “other” employment location category.

TABLE 4.1 AAS Membership Statistics by Discipline, Field, and Location for 1989 and 1997

	1989		1997	
Total Number of Entries	714		599	
With discipline	644	(90.2%)	541	(90.3%)
With field	619	(86.7%)	507	(84.6%)
With location	654	(91.6%)	596	(99.5%)
Discipline Summary				
Observational radio or SMM	13.7	± 1.5%	10.4	± 1.4%
Observational IR	7.6	± 1.1%	5.7	± 1.0%
Observational optical	36.5	± 2.4%	34.6	± 2.5%
Observational UV	5.0	± 0.9%	6.5	± 1.1%
Observational HEA	5.6	± 0.9%	8.7	± 1.3%
Experimental particles and fields	1.1	± 0.4%	1.3	± 0.5%
Laboratory astrophysics	2.2	± 0.6%	2.2	± 0.6%
Theory	23.8	± 1.9%	23.9	± 1.8%
Administration	1.7	± 0.5%	3.5	± 0.8%
Amateur or historian	2.6	± 0.6%	3.0	± 0.7%
Aeronomy or atmospheric science	0.3	± 0.2%	0.4	± 0.3%
Field Summary				
Planetary	15.0	± 1.6%	11.6	± 1.5%
Solar	10.3	± 1.3%	10.7	± 1.4%
Stellar	29.9	± 2.2%	25.4	± 2.2%
ISM + the Galaxy	4.4	± 0.8%	8.3	± 1.3%
Galaxies + clusters	10.7	± 1.3%	12.2	± 1.6%
Active galactic nuclei	10.5	± 1.3%	7.5	± 1.2%
Star and planet formation	6.3	± 1.0%	5.7	± 1.1%
Instrumentation	5.5	± 0.9%	8.1	± 1.3%
Cosmology	5.8	± 1.0%	8.7	± 1.3%
Fundamental experimental	1.6	± 0.5%	1.8	± 0.6%
Location Summary				
Research university	47.4	± 2.7%	47.5	± 2.8%
College	8.4	± 1.1%	10.1	± 1.3%
FFRDC or equivalent	9.9	± 1.2%	11.2	± 1.4%
Government laboratory	18.8	± 1.7%	19.8	± 1.8%
Private	3.8	± 0.8%	2.7	± 0.7%
Industry	8.0	± 1.1%	6.0 ±	1.0%
Other (amateur, retired)	3.7	± 0.7%	2.7	± 0.7%

NOTE: Acronyms are defined in Appendix H.

Table 4.1 shows the estimated percentages of AAS full members by discipline and field for 1989 and 1997. The numbers represent the numbers in the actual subsamples; the 1989 subsample is larger than the 1997 subsample by construction, not because the membership declined between these two years. Optical and infrared observational astronomers constitute approximately 40 percent of research astronomers; radio astronomers, about 12 percent; the other observational fields, about 13 percent; theory, about 25 percent; and the remaining 10 percent, astronomers involved in fundamental measurements, laboratory astrophysics, administration, atmospheric physics, and the history of science. Between 1989 and 1997 there were slight decreases in the fraction of astronomers involved in optical, infrared, and radio observations and increases in the fractions involved in ultraviolet and in high-energy astrophysics. Most of these differences are within the sampling errors of this survey, with the possible exception of the decline in the fraction of radio astronomers, slightly more than a 1.6 sigma result.

By field, the largest number of astronomers are working on stellar astronomy. There appear to be marginally significant decreases in the fraction of planetary and stellar astronomers (1.6 and 1.5 sigma, respectively) and astronomers working on active galactic nuclei that are balanced by increases in the fraction of astronomers working in cosmology, the interstellar medium, and the galaxy and in instrumentation. Extragalactic astronomy as a whole, encompassing the fields of galaxies and clusters, active galactic nuclei (AGN), and cosmology, was pursued by approximately 27 percent of astronomers in 1989, a figure that grew by slightly less than 1 sigma to 28.4 percent in 1997. Again, these changes are at the margin of what is statistically significant, especially because it is often difficult to draw the distinctions between, for example, astronomers working on AGN themselves or using AGN to study cosmology or astronomers studying the interstellar medium (ISM) and those concerned with the connection of the ISM to star formation. Aggregation into broader categories would probably show less significant changes.

Lastly, slightly less than 60 percent of all research astronomers as judged by their enrollment as full members of the AAS are employed at colleges and universities, including both private and state; a little less than one-half are at research universities. Approximately 30 percent are employed at federally funded laboratories including NASA centers, the National Observatories, the Smithsonian Astrophysical Observatory (SAO), and other Federally Funded Research and Development Centers (FFRDCs). The remainder are split between private observatories, industry, self-employment, and retirement. The statistics show essentially no change in employment locations for astronomers over the eight-year period between samples. The differences are all within the sampling errors. There appear to be both robustness and inertia in the field. The small changes noted may well be the result of individual mobility (i.e., changing fields or disciplines as a result of changing opportunities, either funding or scientific).

The committee also addressed the question of what fraction of ground-based optical or IR observers have access to their own telescopes. In the AAS membership subsamples for 1989 and 1997, between 200 and 300 astronomers were classified as observational optical or observational infrared (including solar observers). In 1989, the fraction of OIR observers without direct access to 2-meter-class telescopes or larger was 58 percent. By 1997, with the establishment of several new university and university-National Optical Astronomy Observatories (NOAO) consortia, and counting telescopes now under construction, this fraction had dropped to slightly less than one-half (48 percent). Given that roughly 10 percent of astronomers are at small colleges and another 30 percent or so are at FFRDCs and government laboratories such as the Goddard Space Flight Center (GSFC) or the Space Telescope Science Institute (STScI), it is, however, unlikely that this fraction will ever drop below approximately 40 percent.

4.2 PUBLICATIONS AND DISTRIBUTION OF FUNDING SOURCES

Many studies have been made of the growth of publications by field. The astronomical literature continues to grow almost exponentially. From 1985 to 1996, there was an 85 percent increase in the number of pages published in the five main astronomical journals sampled by Abt (H. Abt, *Publications of the Astronomical Society of the Pacific* 110, 210, 1999).

The committee assessed trends in publication rates by discipline and field and also by funding source. To sample publications, the first volume published in October of 1986, 1989, 1992, 1995, and 1997 was examined for the following journals: the *Astrophysical Journal* (including Letters and Supplement), the *Astronomical Journal, Monthly Notices of the Royal Astronomical Society, Publications of the Astronomical Society of the Pacific, Icarus, Nature, Science, Physical Review D,* and *Physical Review Letters.* This sample contained 884 publications, or an average of 177 for each of the five years considered. The sample attempts to include planetary research by including *Icarus,* and high-energy or particle astrophysics by including *Physical Review Letters* and *Physical Review D,* but it is clearly not representative of solar research. It also slightly undersamples those fields that publish primarily in journals that appear more than once a month (*Nature,* the *Astrophysical Journal, Physics Review D, Monthly Notices of the Royal Astronomical Society, Science*).

Each article was assigned to one or more disciplines and fields and to one or more funding sources. The codes for discipline and field were developed from an initial reading of the literature and were also used to classify astronomers and grants. Funding agencies were identified from acknowledgments at the end of each article. The committee suspects that this method is incomplete, because some authors do not acknowledge funding sources.

4.3 DATA AND CONCLUSIONS

Figure 4.3 shows the fraction of publications in each field. There is little trend in the distribution of fields, except for a slight decline early in stellar, which nonetheless continues to dominate the fraction of publications. Note that Figure 4.3 has two panels simply to avoid confusion and that the upper panel has an expanded scale.

Figure 4.4 shows the fraction of publications in each discipline, again using two panels and an expanded scale in the top panel. There are marginal declines in the radio and ultraviolet publication fractions. Publications concerning optical observations and theory continue to dominate the overall publication rate, just as the numbers of optical or infrared observers and theorists dominate the population of astronomers. The dip in high-energy papers in 1989 is probably real and probably represents the lull between the last of the High Energy Astrophysics Observatory and Einstein analysis, large satellites launched in the late 1970s, and new x-ray data from the German ROSAT, launched in 1990.

Figure 4.5 plots the fraction of papers funded by different sources. “Other federal” is usually dominated by DOE but includes the Department of Defense (DOD) and the individual military services, the North Atlantic Treaty Organization (NATO), and the Smithsonian. The main trends are that an increasing fraction of papers cite support by NASA and foreign agencies, whereas the fraction citing NSF support has declined.

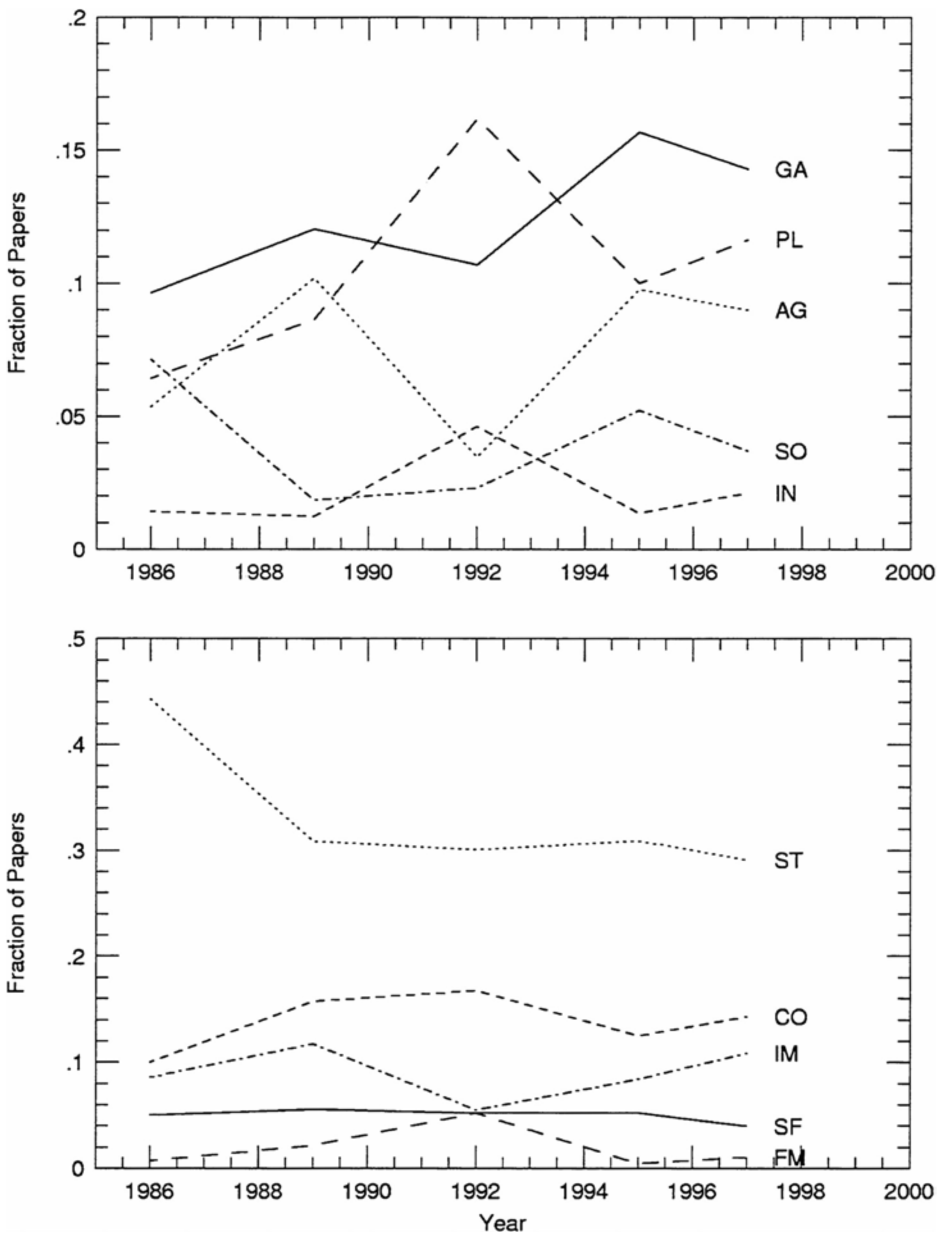

FIGURE 4.3 Fraction of publications by field in 11 selected journals. NOTE: AG - active galactic nuclei; CO - cosmology; FM - fundamental measurements; GA - galaxies; IM - interstellar matter; IN - instrumentation; PL - planetary; SF - star formation; SO - solar; and ST - stellar.

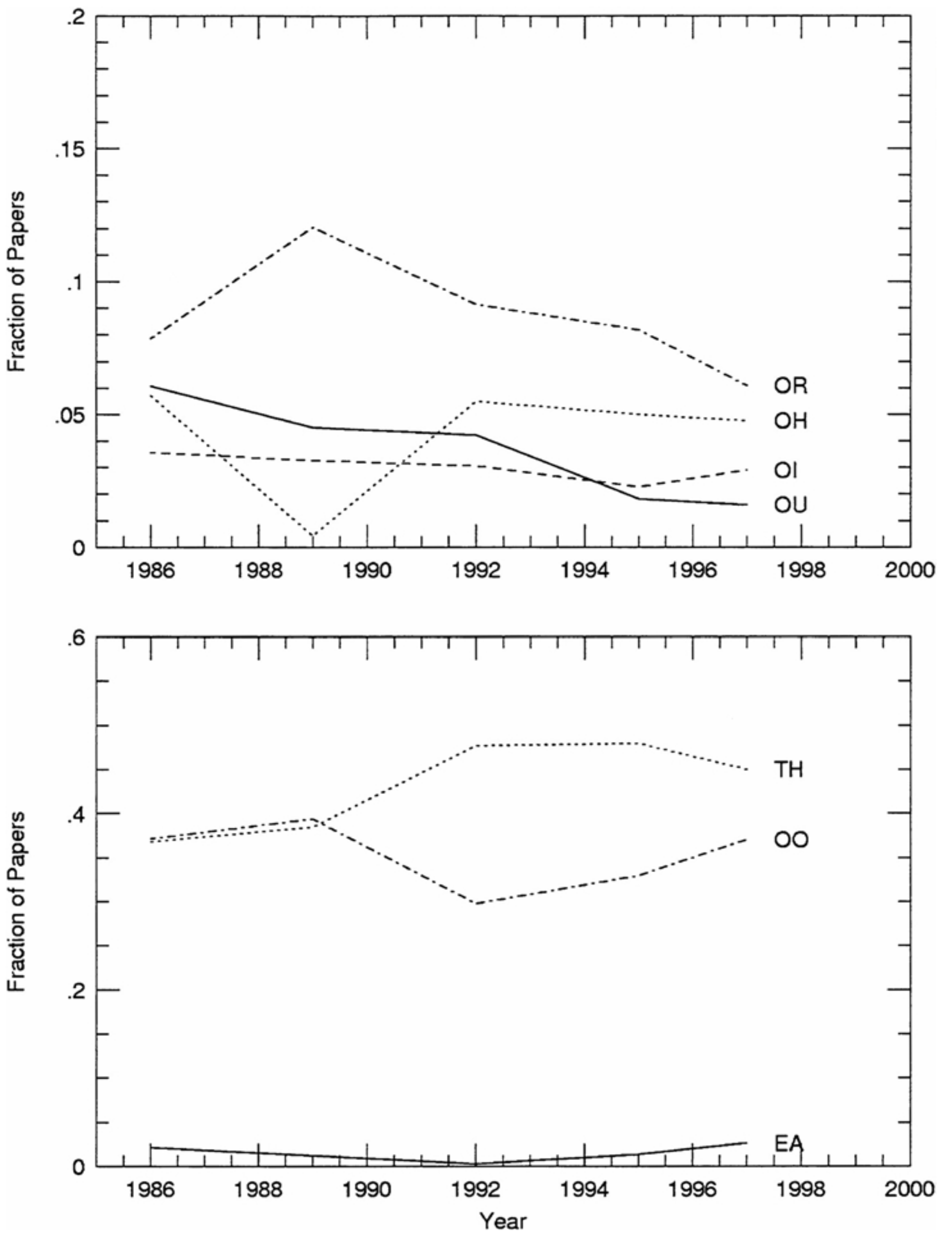

FIGURE 4.4 Fraction of publications by discipline in 11 selected journals. NOTE: EA - experimental astrophysics; OH - observational high energy; OI - observational infrared; OO - observational optical; OR - observational radio; OU - observational ultraviolet; and TH - theory.

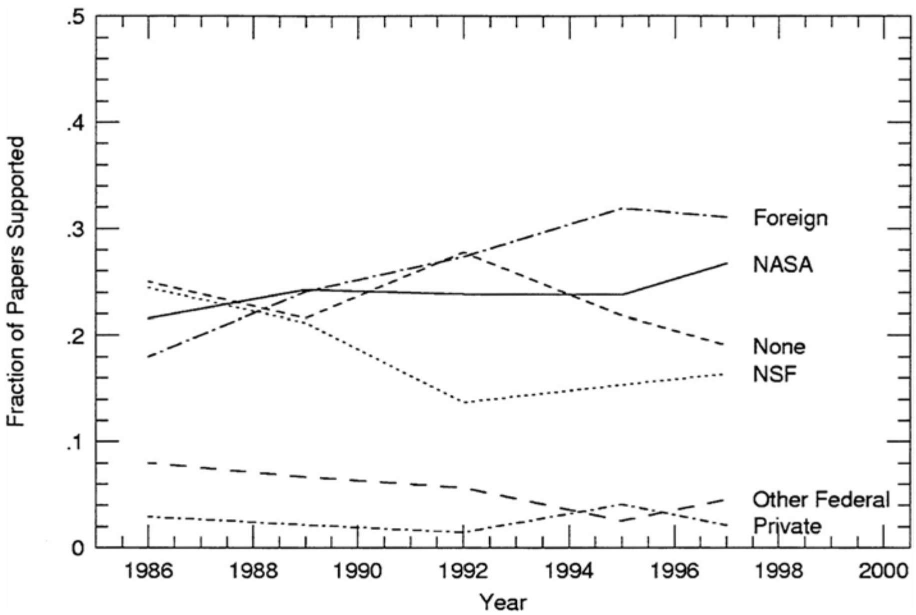

FIGURE 4.5 Fraction of research papers supported by various agencies and institutions.

In Figure 4.6, the panels show the fraction of total papers supported by NSF (solid line) and NASA (dashed line) published in each field. (Note that this is *not* the fraction of the total papers published in each field that were supported by each agency; it is the number of papers in the field that acknowledge agency support divided by the total number of papers in all fields that acknowledge agency support.) The fraction of papers supported by the two agencies is similar in most fields, but NASA dominates planetary (PL) papers and NSF dominates stellar (ST) papers. The only noticeable trends are a decrease in NSF support of ST papers and an increase in both NSF and NASA support of extragalactic (GA) papers. Stellar papers continue to dominate despite the decline, with the exception of 1992, when there was a spike of PL papers. This figure suffers in many fields from small-number statistics.

In summary, the data on both demographics and publications show a modest growth overall and relative stability in the profession over the past 15 years. The strongest trend seen is the increasing role of foreign scientists, indicative of the increasing importance of international collaboration to the profession. Future tracking of these statistics may reveal longer-term trends that are not yet apparent over a 15-year time base.

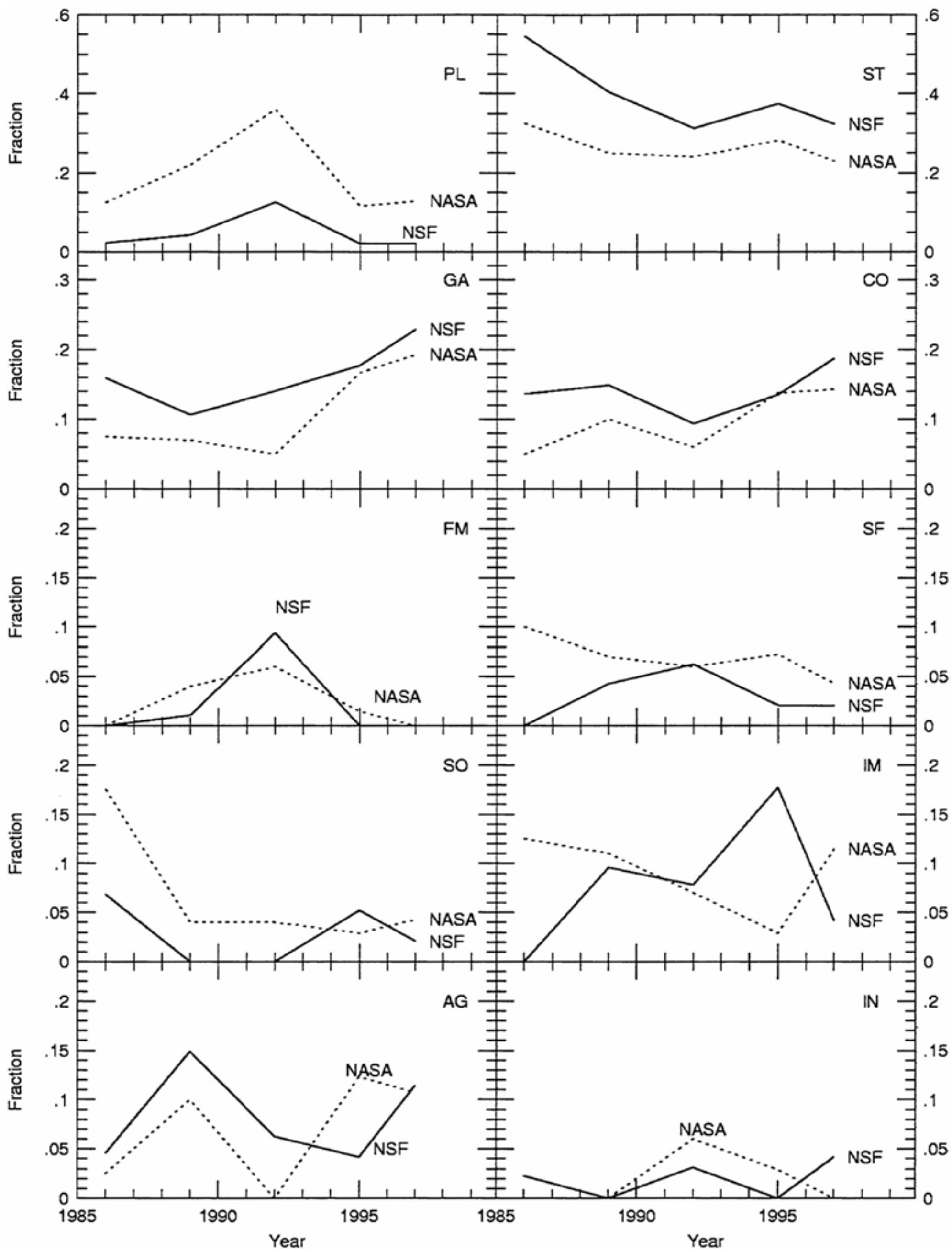

FIGURE 4.6 Fraction of research papers by field supported by NASA and NSF. NOTE: AG - active galactic nuclei; CO - cosmology; FM - fundamental measurements; GA - galaxies; IM - interstellar matter; IN - instrumentation; PL - planetary; SF - star formation; SO - solar; and ST - stellar.

5

Funding

The majority of astronomical research in the United States is funded directly from the astronomy budgets of the NSF and the Office of Space Science (OSS) at NASA. Lesser amounts come from a variety of other sources such as those described in Appendix E.

The direct funding from NASA and NSF falls into four broad categories:

1. *Operations.* This includes operations funding for NASA astronomy missions and for the ground-based observatories of NSF and NASA. NASA funding for these activities is generally the mission operations part of the MO&DA budget.
2. *Instrumentation.* This includes support for instrumentation, both advanced technology instrumentation and facility instrumentation, plus technology development at both NSF and NASA.
3. *Science and Analysis Support.* This includes support for the observations, data analysis, and astronomical theory programs at NASA and for the individual investigator grants program of NSF. At NASA, funding for this category comes both from the data analysis (DA) part of MO&DA and from NASA's R&A budget.
4. *Construction.* This includes major facility or mission design, development, and construction, such as the construction of AXAF/Chandra by NASA and the Very Long Baseline Array (VLBA) facility, the Gemini telescopes, and the Green Bank Telescope (GBT) by NSF. At NSF, major construction is included in the major research equipment (MRE) program line.

Figure 2.2 in Chapter 2 provides a broad overview of astronomy funding since 1981 with program plan projections for FY 1999. The following sections deal with more detailed aspects of the NSF and NASA budgets. For NSF, the committee considers the Division of Astronomical Sciences (AST) budget in total and comments only briefly on extradivisional funding for the construction of facilities. NSF funding for MRE construction is decided at the agency level and not in the divisions. For NASA, only the R&A budget is considered, not the capital budgets for mission design, development, construction, and launch. NASA technology development funding is also mentioned briefly.

5.1 THE NSF BUDGET

Astronomy at the National Science Foundation is funded primarily in the AST or in the Mathematics and Physical Sciences (MPS) Directorate. Figure 5.1 and Table 5.1 show the trends in research and related activities (R&RA) funding for NSF as a whole, for the MPS Directorate, and for the AST. Based on figures from the American Association for the Advancement of Science (AAAS), total NSF R&RA funding has grown significantly faster than inflation over the past decade, nonconstruction MPS funding has increased slightly with respect to inflation, and nonconstruction AST funding has fallen behind.

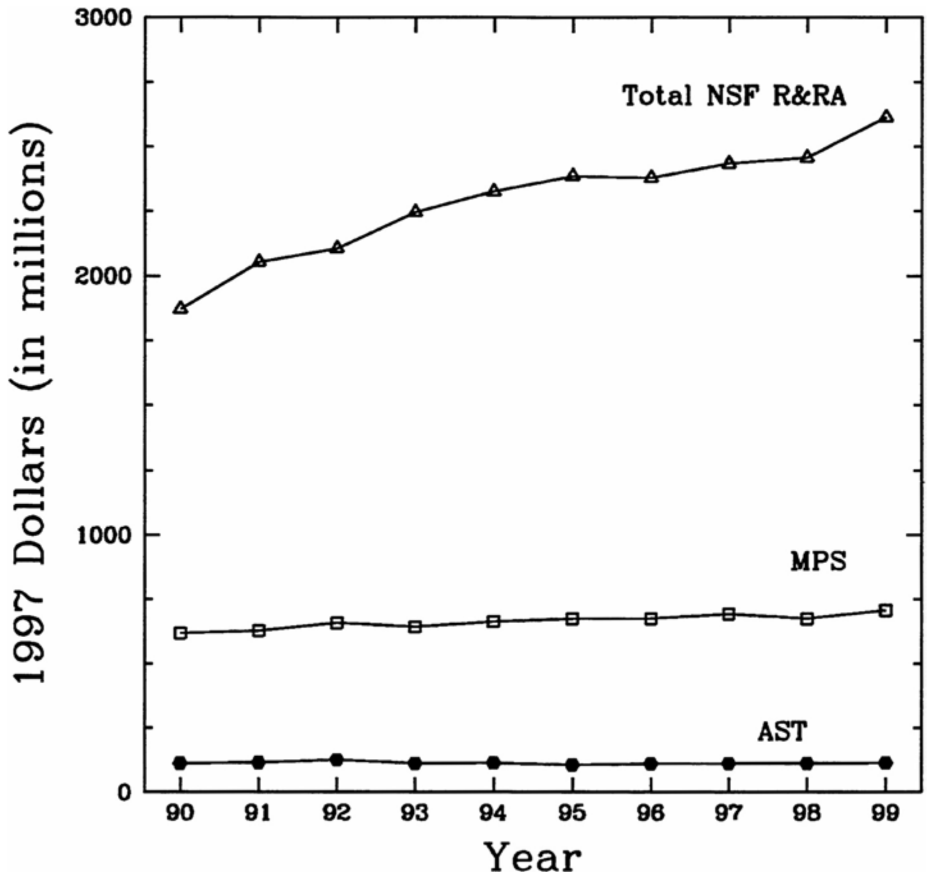

FIGURE 5.1 Total NSF, MPS, and AST funding, FY 1990-1999, in 1997 dollars. Top curve is the total NSF R&RA budget (R. Konkel, from NSF Congressional Budget Summary) and does not include construction. Lower curves are for the MPS Directorate and the AST, also excluding construction (MRE) funding; these lines represent the essential "operating" budgets of the Mathematics and Physical Sciences Directorate and the Division of Astronomical Sciences.

Comparing the last three years of the reporting period to the first three years, NSF R&RA increased approximately 15 percent relative to inflation, the MPS line (without MRE) increased 9 percent, and AST decreased 5 percent. Part of this relative change is due to small increments to the AST budget early in the decade for infrastructure, and a large part is due to the creation of new R&RA programs and new priorities at NSF including the MRE construction line, which is separate from MPS or AST. Note that some funding for astrophysics, particularly for theory, atomic and molecular physics, submillimeter and IR astronomy at the South Pole, and solar physics, comes from outside the AST budget (primarily from the NSF MPS, OPP (Office of Polar Programs), and ATM (Division of Atmospheric Sciences). Table 5.2 shows the detailed funding of these other areas. Astronomy as a whole at the NSF has benefited significantly from the MRE program as detailed below, but the base NSF "operating" budget for astronomy has declined, relative to other components of the NSF.

TABLE 5.1 NSF Budget Totals in Millions of 1997 Dollars, 1990 to 1999

Year	AST		AST+MRE[a]		Other NSF[b]		MPS		MPS+MRE		NSF R&D
	Budget	%	Budget	%	Budget	TA%[c]	Budget	%	Budget	%	
1990	112.85	(5.4)	125.72	(6.0)	18.87	(7.5)	618.64	(29.7)	623.947	(30.0)	2,080.626
1991	115.21	(5.3)	212.33	(9.7)	21.90	(10.7)	627.61	(28.6)	653.766	(29.8)	2,193.511
1992	126.69	(5.7)	150.00	(6.8)	23.32	(7.8)	658.06	(29.6)	700.788	(31.6)	2,220.720
1993	112.23	(5.1)	127.68	(5.8)	23.99	(6.9)	643.10	(29.1)	680.461	(30.8)	2,210.757
1994	114.00	(4.7)	132.25	(5.5)	25.34	(6.5)	662.96	(27.5)	681.223	(28.3)	2,406.653
1995	106.77	(4.3)	149.66	(6.0)	25.15	(7.0)	674.94	(26.9)	806.695	(32.2)	2,506.276
1996	110.74	(4.5)	110.74	(4.5)	28.40	(5.7)	675.37	(27.6)	746.932	(30.6)	2,444.785
1997	112.73	(4.7)	112.73	(4.7)	27.77	(5.8)	693.45	(28.6)	748.500	(30.9)	2,424.000
1998	111.62	(4.6)	125.47	(5.1)	29.73	(6.3)	675.09	(27.5)	731.400	(29.0)	2,456.778
1999[d]	114.15	(4.4)	122.81	(4.7)	26.34	(5.7)	706.83	(27.1)	736.670	(28.2)	2,612.127

NOTE: Acronyms are defined in Appendix H.

[a] These numbers include VLBA construction, which was authorized before the MRE account was created in 1991, and the GBT, a special construction project authorized in full in 1991. They do not include LIGO, which was motivated primarily by the physics community.

[b] Other NSF funding for astronomy from the MPS Directorate, OPP, and OMA.

[c] Total astronomy percent.

[d] 1999 numbers are as planned for the program.

TABLE 5.2 Other NSF Astronomy and Astrophysics Support in Millions of 1997 Dollars, 1990 to 1999

Year	Physics	OPP	OMA	ATM	Total Other [a]	PHY MRE+OC [b]	LIGO OPS [c]
1990	9.39	0.70	0.00	8.78	18.87	0.00	0.00
1991	9.44	3.60	0.00	8.86	21.90	80.56	0.00
1992	9.59	4.48	0.00	9.25	23.32	17.91	0.00
1993	9.77	4.58	0.00	9.64	23.99	21.95	0.00
1994	9.98	5.23	0.00	10.13	25.34	0.00	0.00
1995	10.17	5.13	0.00	9.85	25.15	88.91	0.00
1996	10.39	5.17	3.06	9.78	28.40	71.58	0.00
1997	10.62	5.24	1.90	10.01	27.77	55.00	0.30
1998	10.64	5.16	3.86	10.07	29.73	25.54	7.43
1999	9.77	5.58	0.87	10.12	26.34	0.00	21.61

NOTE: Acronyms are defined in Appendix H.

[a] Does not include LIGO or LIGO operations.
[b] Physics MRE (LIGO) plus GBT construction.
[c] LIGO operations.

5.1.1 Total NSF R&RA Budget and AST and MPS Fractions

Table 5.1 compares the AST and AST + MRE and the MPS and MPS + MRE budgets to the total NSF R&D budget for 1990 to 1999. The total NSF R&D budget is taken from the AAAS summary and includes NSF R&RA plus MRE construction funding (hence, the R&D label); the AST and MPS budgetary figures are from those NSF units. The number in parentheses is the fraction of the total NSF R&RA budget that the figure given represents for each year. Funding for astronomy and astrophysics from outside the AST line is also included. The level of non-AST (and nonconstruction) NSF funding for astronomy averaged around 20 percent of the AST budget level over the past decade, except for an increase in the last two years associated with the start of LIGO operations.

The NSF AST line, not including MRE construction funding, averaged 5.5 percent of the NSF budget in the first three years of the decade and only 4.6 percent in the last three, a relative decrease of approximately 20 percent. Including the highly variable MRE funding (but not LIGO), AST + MRE represented approximately 7.7 percent of the NSF budget in the first three years and 4.8 percent in the last three, a relative decrease of approximately 30 percent. Including the NSF funding of astronomy and astrophysics outside AST and neglecting the year in which $80 million was provided for the GBT, the average for three of the first four years of the decade was 7.3 percent of the NSF R&D budget, and 5.9 percent for the last three. Similarly, MPS and MPS + MRE averaged 29.3 and 30.5 percent of the NSF budget at the beginning of the decade, and 27.7 and 29.4 percent at the end, relative decreases of only approximately 6 and 4 percent, respectively.

A further breakdown of the overall NSF budget for astronomy is given in Table 5.3 in current-year dollars and in Table 5.4 in 1997 dollars. Other sources of the budget for astrophysics at NSF are detailed in Table 5.5 in current-year dollars and in Table 5.6 in 1997 dollars. The deflators used to convert into 1997 dollars are given in Appendix E. The budget figures for FY 1999 are estimates. Most astronomy research funded by the NSF is contained in the AST budget.

Overall funding for astronomy at the NSF through the AST has not kept pace with inflation even when adjustments are made for infrastructure additions to the National Radio Astronomy Observatory (NRAO) budget in the early 1990s (see below).

TABLE 5.3 **NSF Division of Astronomical Sciences Budget for FY 1990 to FY 1999 in Thousands of Current-Year Dollars**

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
ATI	6,315	6,820	8,572	7,883	8,702	8,066	7,100	7,980	5,938	
MRI	—	—	—	—	—	—	—	—	1,355	
Facility	—	—	—	—	—	—	2,450	208	617	
Total instrumentation	6,315	6,820	8,572	7,883	8,702	8,066	9,550	8,188	7,910	7,300
Extragalactic	6,318	6,748	7,319	6,673	8,462	7,117	6,625	7,237	7,775	
Galactic	3,558	3,695	3,834	3,683	3,990	3,557	3,560	4,115	3,800	
Planetary	1,137	1,058	1,068	537	1,461	1,499	1,280	1,812	1,718	
Particle	—	—	—	—	—	—	—	—	5	
Stellar	5,161	5,512	6,020	6,213	6,278	6,381	5,999	6,145	6,417	
STC	2,058	2,050	2,300	2,442	2,544	2,540	2,540	2,540	2,108	
CDP	1,052	—	—	—	—	—	—	—	—	
ESP[a]	—	—	—	—	1,993	1,937	2,388	3,316	4,139	
KDI	—	—	—	—	—	—	—	—	448	
LEXEN	—	—	—	—	—	—	—	580	—	
Total research	19,284	19,062	20,541	19,547	24,728	23,031	22,392	25,745	26,410	26,000
University radio	7,001	7,634	8,038	8,538	7,270	7,055	7,055	7,440	7,000	
NRAO	30,204	31,108	34,465	29,215	29,021	29,370	30,005	30,000	30,513	31,840
NAIC	6,219	8,532	10,903	9,475	8,640	7,709	8,292	8,265	8,265	8,950
RSM	100	98	118	95	82	90	89	93	197	
NOAO	24,402	25,524	28,386	27,461	27,740	26,700	270,182	27,630	27,891	29,000
Gemini operations	—	—	—	—	—	—	3,600	5,100	6,250	7,130
Total operations	67,926	72,896	81,910	74,784	72,753	70,924	76,059	78,528	80,116	84,600
Undistributed[b]	249	644	1,477	31	60	50	302	266	294	700
AST total	93,774	99,422	112,500	102,245	106,243	102,071	108,303	112,727	114,730	118,600
VLBA	10,700	10,300	8,700	—	—	—	—	—	—	—
Gemini	—	4,000	12,000	14,070	17,013	41,000	—	—	4,000	—
ALMA design and development	—	—	—	—	—	—	—	—	9,000	9,000
GBT	—	69,520	—	—	—	—	—	—	—	—
Total construction	10,700	83,820	20,700	14,070	17,013	41,000	—		13,000	9,000

NOTE: Acronyms are defined in Appendix H.

[a] Includes CAREER, PECASE, and POWRE awards.

[b] Includes undistributed funds and special programs reserve.

TABLE 5.4 **NSF Division of Astronomical Sciences Budget for FY 1990 to FY 1999 in Thousands of 1997 Dollars**

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
ATI	7,599	7,903	9,653	8,653	9,337	8,437	7,260	7,980	5,833	
MRI	—	—	—	—	—	—	—	—	1,331	
Facility	—	—	—	—	—	—	2,505	208	606	
Total instrumentation	7,599	7,903	9,693	8,653	9,337	8,437	9,765	8,188	7,770	7,026
Extragalactic	7,603	7,818	8,242	7,324	9,079	7,445	6,774	7,237	7,638	
Galactic	4,282	4,282	4,318	4,043	4,281	3,721	3,640	4,115	3,733	
Planetary	1,368	1,226	1,203	589	1,569	1,568	1,309	1,812	1,688	
Particle	—	—	—	—	—	—	—	—	5	
Stellar	6,211	6,387	6,779	6,820	6,736	6,675	6,134	6,145	6,304	
STC	2,477	2,375	2,590	2,681	2,730	2,657	2,597	2,540	2,071	
CDP	1,266	—	—	—	—	—	—	—	—	
ESP[a]	—	—	—	—	2,138	2,026	2,442	3,316	4,066	
KDI	—	—	—	—	—	—	—	—	440	
LEXEN	—	—	—	—	—	—	—	580	—	
Total research	23,206	22,088	23,132	21,457	26,532	24,091	22,896	25,745	25,943	25,024
University radio	8,425	8,846	9,052	9,372	7,800	7,380	7,214	7,440	6,876	
NRAO	36,347	36,046	38,812	32,069	31,138	30,722	30,680	30,000	29,973	30,645
NAIC	7,484	9,886	12,278	10,401	9,270	8,064	8,479	8,265	8,119	8,614
RSM	120	114	133	104	88	94	91	93	194	
NOAO	29,365	29,576	31,966	30,144	29,764	27,928	27,625	27,630	27,398	27,911
Gemini operations	—	—	—	—	—	—	3,681	5,100	6,139	6,862
Total operations	81,740	84,468	92,241	82,090	78,061	74,188	77,770	78,528	78,699	81,424
Undistributed[b]	300	746	1,663	34	64	52	309	266	289	674
AST total	112,845	115,205	126,689	112,234	113,995	106,769	110,739	112,727	112,701	114,148
VLBA	12,876	11,935	9,797	—	—	—	—	—	—	—
Gemini	—	4,635	13,514	15,445	18,254	42,887	—	—	3,929	—
ALMA design and development	—	—	—	—	—	—	—	—	8,841	8,662
GBT	—	80,556	—	—	—	—	—	—	—	—
Total construction	12,876	17,135	14,311	14,070	18,254	42,887	—	—	12,770	8,662

NOTE: Acronyms are defined in Appendix H.

[a] Includes CAREER, PECASE, and POWRE awards.
[b] Includes undistributed funds and special programs reserve.

TABLE 5.5 NSF Other Astrophysics Budget for FY 1990 to FY 1999 in Thousands of Current-Year Dollars

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
MPS Astronomy	7,800	8,150	8,520	8,900	9,300	9,720	10,160	10,620	11,100	11,400
OPP	580	3,110	3,980	4,170	4,870	4,900	5,060	5,240	5,250	5,800
OMA	—	—	—	—	—	—	2,990	1,900	3,930	900
ATM	7,300	7,650	8,210	8,780	9,440	9,420	9,560	10,010	10,250	10,510
Total other	15,680	18,910	20,710	21,850	23,610	24,040	27,770	27,770	30,530	28,610
LIGO operations	`	`	`	`	`	`	`	300	7,300	20,800
LIGO	`	`	15,900	20,000	`	85,000	70,000	55,000	26,000	`
Total other construction	—	—	15,900	20,000	—	85,000	70,000	55,000	26,000	—

NOTES: Acronyms are defined in Appendix H. LIGO operations have been ramping up since 1997 (figures from the LIGO project).

TABLE 5.6 NSF Other Astrophysics Budget for FY 1990 to FY 1999 in Thousands of 1997 Dollars

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
MPS Astronomy	9,390	9,440	9,590	9,770	9,980	10,170	10,390	10,620	10,639	9,769
OPP	700	3,600	4,480	4,580	5,230	5,130	5,170	5,240	5,160	5,580
OMA	—	—	—	—	—	—	3,060	1,900	3,860	870
ATM	8,780	8,860	9,250	9,640	10,130	9,850	9,780	10,010	10,070	10,120
Total other	18,870	21,900	23,320	23,990	25,340	25,150	28,400	27,770	29,729	26,339
LIGO operations	`	`	`	`	`	`	`	300	7,431	21,611
LIGO	`	`	17,905	21,954	`	88,912	71,575	55,000	25,540	`
Total other construction	—	—	17,905	21,954	—	88,912	71,575	55,000	25,540	—

NOTE: Acronyms are defined in Appendix H.

5.1.2 NSF AST Overview

Figure 5.2 is the graphic representation of the NSF AST budget since 1990, broken into the three major nonconstruction categories. Shown is the total AST budget, not including the MRE capital funding for Gemini, the GBT, or the MMA/ALMA, as well as the budgets for operations, instrumentation, and research. Major construction is not currently part of the NSF AST budget but rather falls in the NSF MRE budget. It is included at the end of Table 5.3 and Table 5.4. The university-operated radio facilities were included in the scientific discipline grants programs before 1994, but these amounts have been moved from the research grants to the facilities line for consistency.

In 1997 dollars, the NSF AST budget was relatively flat over the decade, except for the infrastructure enhancement in 1992. Declines occurred during the middle of the decade in operations support for the national radio and optical observatories and the university radio observatories, although the downward trend of the first five years of the decade was reversed in the last four. The slight bump in the operations budgets in 1992 was due to funds provided to NRAO and the National Astronomy and

Atmospheric Center (NAIC) for infrastructure as recommended in the 1991 Decadal Report. Instrumentation funding was flat or slightly declining, and the individual grants program saw a modest 10 to 12 percent increase over inflation during the same period. This can be tracked to the current inclusion in the AST budget of the Presidential Young Investigator (PYI; now CAREER) awards program. Even with the inclusion of these programs, research grants to individual investigators accounted for less than 22 percent of the NSF astronomy budget.

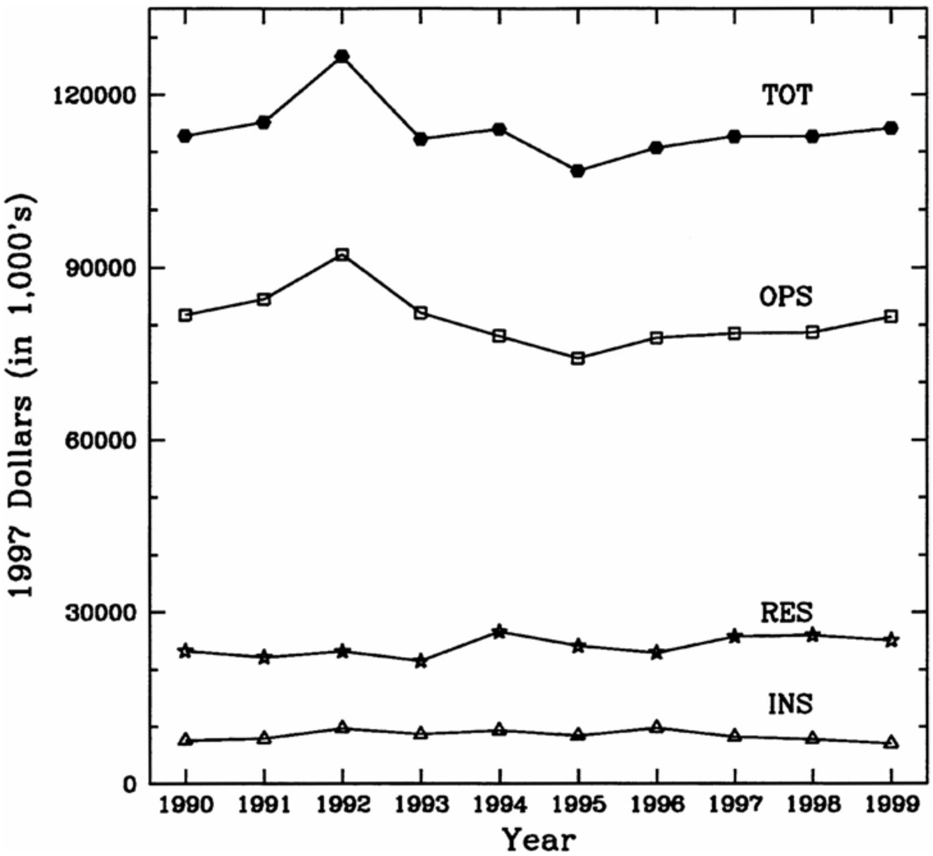

FIGURE 5.2 NSF Division of Astronomical Sciences budget in 1997 dollars. The top curve is the total AST budget. Lower curves are for total operations (OPS), research grants (RES), and instrumentation grants (INS) expenditures. Operation of private radio facilities is included in the operations line. The AST budget line does not include major construction funding under the MRE program. SOURCE: NSF.

NSF funding for instrumentation was basically flat in 1997 dollars during the 1990s, with the exception of a one-year increment in 1996 for the facility instrumentation program. Gains in funding through that program and through the Major Research Instrumentation (MRI) program were offset by losses in the long-running Advanced Technology and Instrumentation (ATI) program, despite the strong recommendation of the 1995 NRC report *A Strategy for Ground-Based Optical and Infrared Astronomy* to increase instrumentation funding to properly utilize the significant increases in telescope collecting area available as the result of new, large-telescope construction from 1993 to 2003.

NSF's AST has four primary “field” subdivisions: extragalactic, galactic, planetary, and stellar. Within these fields, there has been a modest decrease in funding for galactic research, and an increase for planetary, while stellar and extragalactic have remained relatively flat (see Table 5.4).

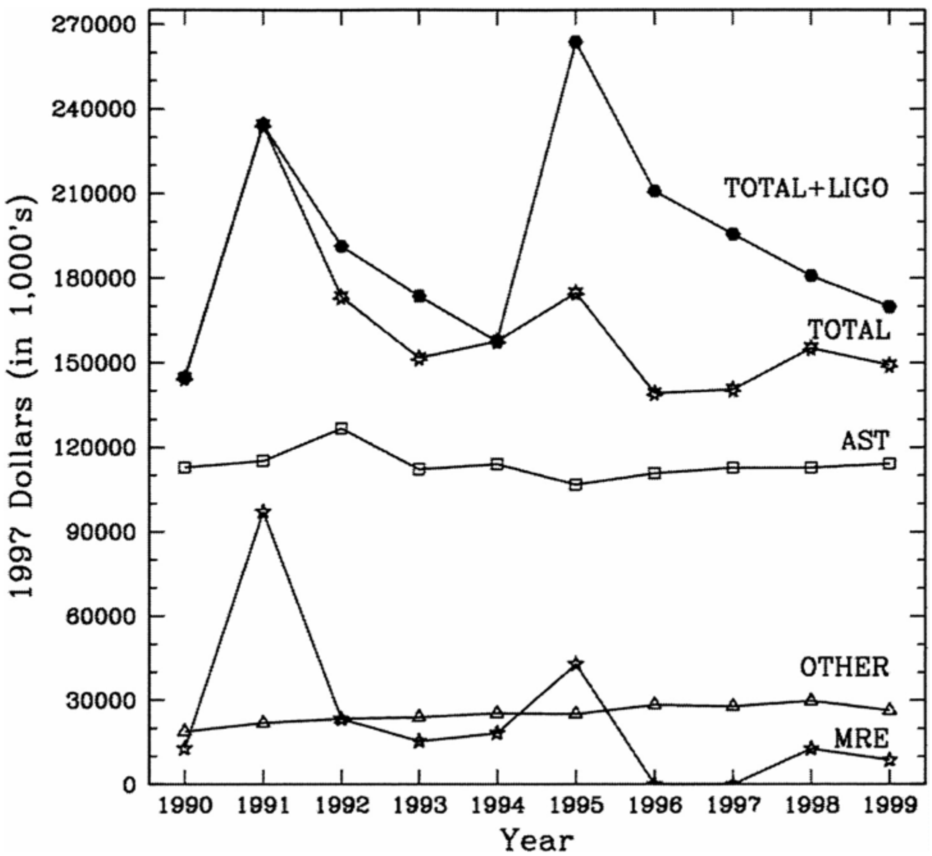

FIGURE 5.3 Total NSF budget for astronomy and astrophysics in 1997 dollars, 1990 to 1999. The top curve is the total of the budget for AST, MRE, other, and LIGO. LIGO support is included in this total, but not in astronomy-related MRE, since this is primarily a physics program. The next curve down is 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: NSF.

In the operations budget, various lumps in the funding histories of the national observatories are associated with intermediate to small construction projects. For example, the large excess for NRAO in 1990 was the funding to repair the telescope tracks, and in the NAIC budget in and around 1992, funding for the Arecibo upgrade. The NSF budget has separate line items for the construction for Gemini, the GBT, and now ALMA. The U.S. share of operations support for Gemini as a separate line item was one of the major recommendations of the 1995 OIR strategy report. A reasonable fraction of the Gemini operations line is dedicated to instrumentation development, but the access and administrative costs for U.S. astronomers (telescope time allocations, U.S. science oversight, etc.) are contained in the NOAO budget.

Note that, including operations for the national and university radio observatories and grants funding, slightly less than half of the NSF AST budget during the 1990s was used to support ground-based radio astronomy.

Figure 5.3 recapitulates total NSF funding for astronomy and astrophysics from 1990 to 1999, including both AST MRE and MPS MRE (specifically LIGO) and the additional astronomy- and astrophysics-related funding from MPS, OPP, ATM, and the NSF Office of Multidisciplinary Affairs

(OMA). The spikes in the total funding in 1991 and 1995 are associated with major increments for the construction of the GBT (a lump sum in one year) and LIGO.

5.1.3 Major Research Equipment

In the period under study, three major facilities or telescopes have been funded through the NSF MRE program line and an additional large telescope, the GBT, as a special appropriation. The VLBA, which is described in more detail below, is operated by NRAO, and its construction was funded at the end of last decade and the beginning of this. The U.S. contribution to the twin Gemini 8-meter telescopes and part of their initial instrument complement, $88 million, was funded primarily over five years in the middle of the decade. The initial design and development funding for ALMA, to be operated by NRAO, was obtained in the last few years. Operations support for the VLBA, Gemini, and ALMA is included or to be included in the AST budget.

5.1.4 Grants Program

As part of its study of the NSF grants program for astronomy, the committee assigned categories, similar to those used for the publication and demographic analyses in Section 4.2, to the 1,709 NSF grants in the Division of Astronomical Sciences that were active during FY 1986 to FY 1997. The grant amounts were over the durations of the grants, typically three years, so that the time period covered was not well defined; the funding period on some grants preceded FY 1986 by a few years and, on others, extended beyond FY 1997 by a few years. The results are shown by field in Table 5.7 and by discipline in Table 5.8.

The disciplines listing includes separate entries for the Center for Particle Astrophysics and the university radio observatories. The Center for Particle Astrophysics funded a combination of theoretical, experimental, and observational research. The national observing facilities have been categorized under administrative. The NSF also funds university radio facilities (Haystack, Owens Valley [OVRO], Caltech Submillimeter Observatory [CSO], Five College Radio Astronomy Observatory [FCRAO], the Berkeley-Illinois-Maryland Array [BIMA]), and these are in a separate category. It is clear that the dominant components of NSF funding are directed to ground-based optical and radio observing. Wavelength regions that are best observed from space are funded primarily by NASA. The results indicate that theory is a small part of the NSF AST funding profile, although it is a more substantial part of the funding for individual investigator grants, and a significant amount of theory funding for astrophysics is included in the MPS Physics Division budget.

In the categorization by field, grants were assigned to a topic unless the range of activities in the grant did not allow this. This resulted in an additional category for education, which included general Research Experience for Undergraduates (REU) programs, and one for meetings, which included support for broad meetings. The Center for Particle Astrophysics was assigned to the cosmology category and makes up a significant part of it. With the categorization used here, the instrumentation and stellar fields are the dominant ones.

Note that in Table 5.7, "grants" includes the grant funding for operations at both national and privately run observatories.

TABLE 5.7 Integrated NSF Division of Astronomical Sciences Grants by Field, FY 1986 to FY 1997

Description	Number of Awards	Percentage of Total Awards	All-Year Value (dollars)	Percentage of All-Year Total	Percentage of Total, Excluding Operations
Active galactic nuclei	122	7.1	28,185,072	1.9	7.2
Cosmology	84	4.9	48,986,209	3.4	12.5
Education	18	1.1	2,209,949	0.2	0.6
Experimental particles and fields	14	0.8	2,373,144	0.2	0.6
Galaxies and clusters	253	14.8	54,425,745	3.7	13.9
Interstellar medium	179	10.5	42,099,982	2.9	10.8
Instrumentation	207	12.1	84,893,288	5.8	21.7
Meetings	28	1.6	4,117,071	0.3	1.1
Not applicable	4	0.2	1,027,993	0.1	0.3
Operations	54	3.2	1,064,334,988	73.1	—
Planetary	129	7.5	17,376,983	1.2	4.4
Star formation	57	3.3	10,330,071	0.7	2.6
Solar	54	3.2	8,283,322	0.6	2.1
Stellar	506	29.6	86,820,969	6.0	22.2
Total	1,709	100.0	1,455,464,786	100.0	100.0

TABLE 5.8 Integrated NSF Astronomy Grants, FY 1986 to FY 1997

Description	Number of Awards	Percentage of Total Awards	All Year Value (dollars)	Percentage of All Year Total	Percentage of Total, Individual Investigator
National observatories	7	0.4	975,883,736	67.0	
University radio observatories	43	2.5	117,189,441	8.1	
Center for Particle Astrophysics	2	0.1	23,910,919	1.6	
Administrative, computers, meetings	111	6.5	15,221,893	1.0	
Lab or experimental astrophysics	36	2.1	6,627,461	0.5	2.1
Experimental particles and fields	6	0.4	1,177,622	0.1	0.4
X-ray and gamma ray	18	1.1	3,293,955	0.2	1.0
Observational IR	29	1.7	6,436,037	0.4	2.0
Observational optical	839	49.1	182,489,676	12.5	56.5
Observational radio	217	12.7	46,690,576	3.2	14.4
Observational UV	1	0.1	195,000	0.0	0.1
Theory	400	23.4	76,348,470	5.2	23.6
Total	1,709	100.0	1,455,464,786	100.0	100.0

NOTE: Acronyms are defined in Appendix H.

5.1.5 Oversubscription in the NSF Grants Program

Over the past decade, NSF saw a steady increase in proposal pressure and a constant average grant size (on an annualized basis) when allowance is made for inflation. Working into relatively constant resources, the result has been a deteriorating success rate. These trends are shown in the next four figures. Figure 5.4 shows the overall number of proposals funded versus the number received by NSF's AST.

Figure 5.5 shows the number of successful proposals for AST as a whole and individually for the five main programs (Advanced Technology and Instrumentation, Extragalactic and Cosmology, Galactic Astronomy, Stellar Astronomy and Astrophysics, and Planetary). Although subject to the usual small-number fluctuations, the trends in the number of funded proposals are quite flat.

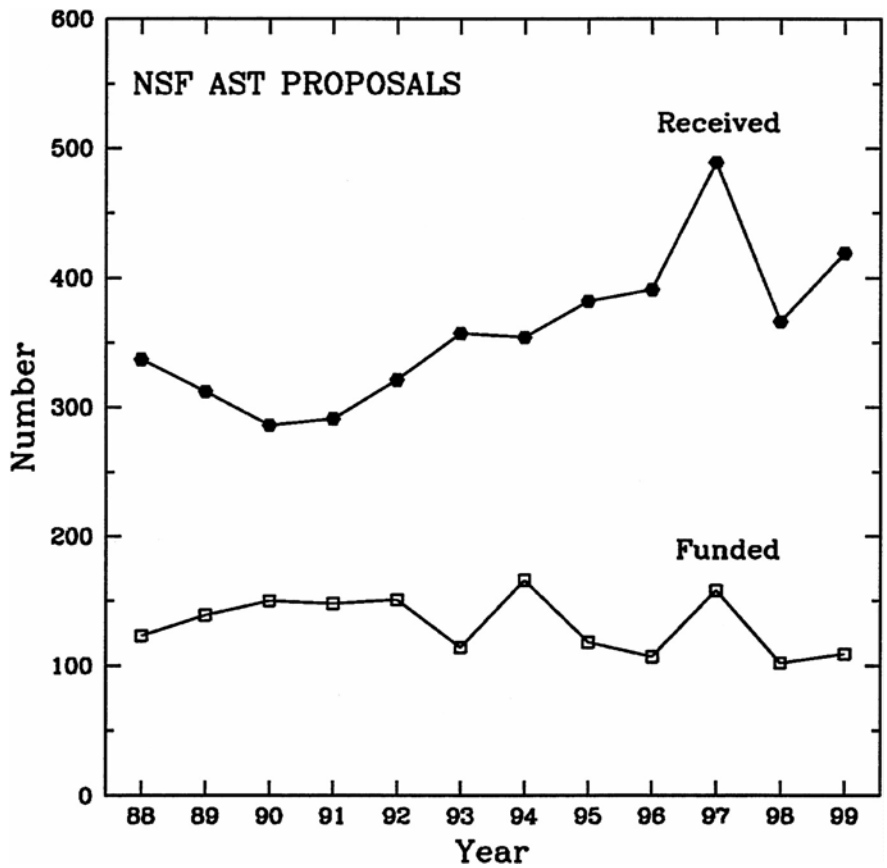

FIGURE 5.4 Overall number of proposals received and funded by NSF AST during the 11-year period from 1988 to 1999. SOURCE: NSF Division of Astronomical Sciences.

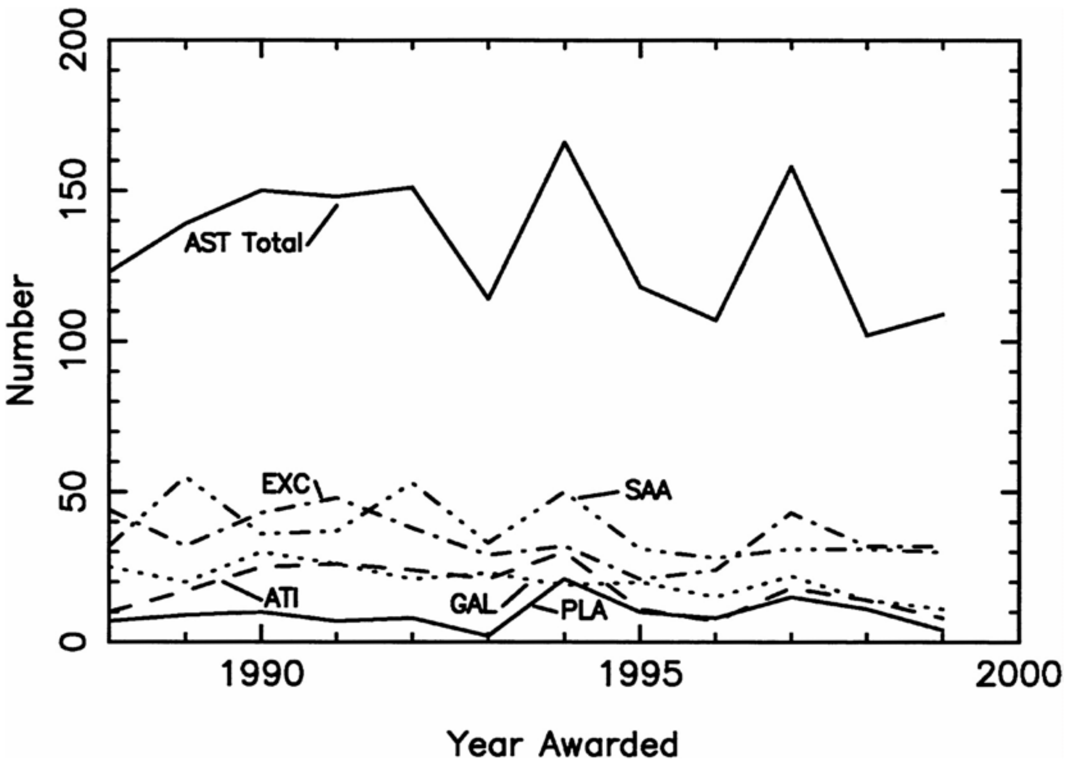

FIGURE 5.5 Number of awards made by NSF AST during the 11-year period. Also shown are the numbers by program: Extragalactic and Cosmology (EXC), Stellar Astronomy and Astrophysics (SAA), Galactic Astronomy (GAL), Advanced Technology and Instrumentation (ATI), and Planetary (PLA). SOURCE: NSF Division of Astronomical Sciences.

Figure 5.6 shows the funding rate given as the number of awards and the proposal success rate for the AST and its research programs. Taken together, Figure 5.4 Figure 5.5 through Figure 5.6 show that the overall success rate in the NSF AST has declined in recent years to approximately 28 percent of the grant proposals submitted, which is below the NSF average of about 33 percent. In some individual programs, the results have been even less favorable. The deterioration in the rate of success is evident, both on the division level and almost without exception in each of the programs. Despite the growth of the field, the number of awards has fallen slightly since the beginning of the decade. This trend is not the result of increases in the average grant size. Figure 5.7 shows the (annualized) median size of each grant. Overall, inflation-adjusted grant sizes remained fairly constant.

Finally, Figure 5.8 shows the average fraction of successful proposals for research and instrumentation grants in the AST compared to the NSF average for competitive grants. Note that there are large statistical fluctuations in the fraction of accepted grants in the AST, which are driven both by relatively small numbers of proposals and by funding cycles that oscillate across fiscal year boundaries. For the AST, two- or three-year averages are appropriate. Early in the decade, the AST average was well above the mean, but it fell below the NSF mean acceptance ratio in two of the last four years.

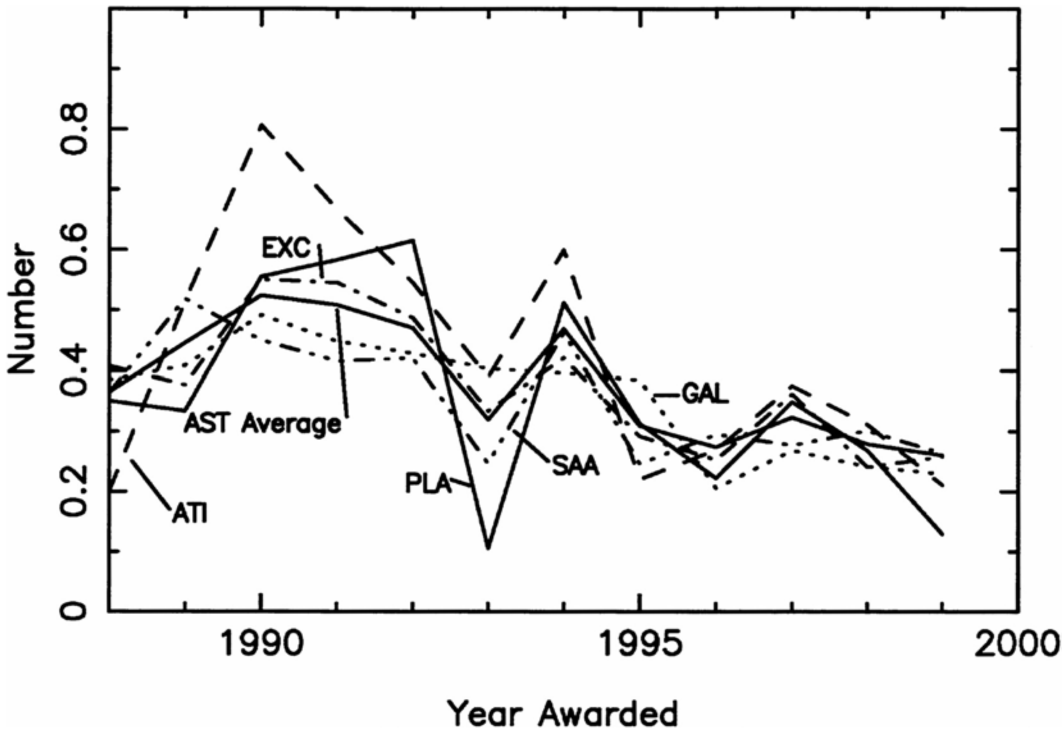

FIGURE 5.6 Proposal success rate for NSF AST and its major programs. SOURCE: NSF Division of Astronomical Sciences.

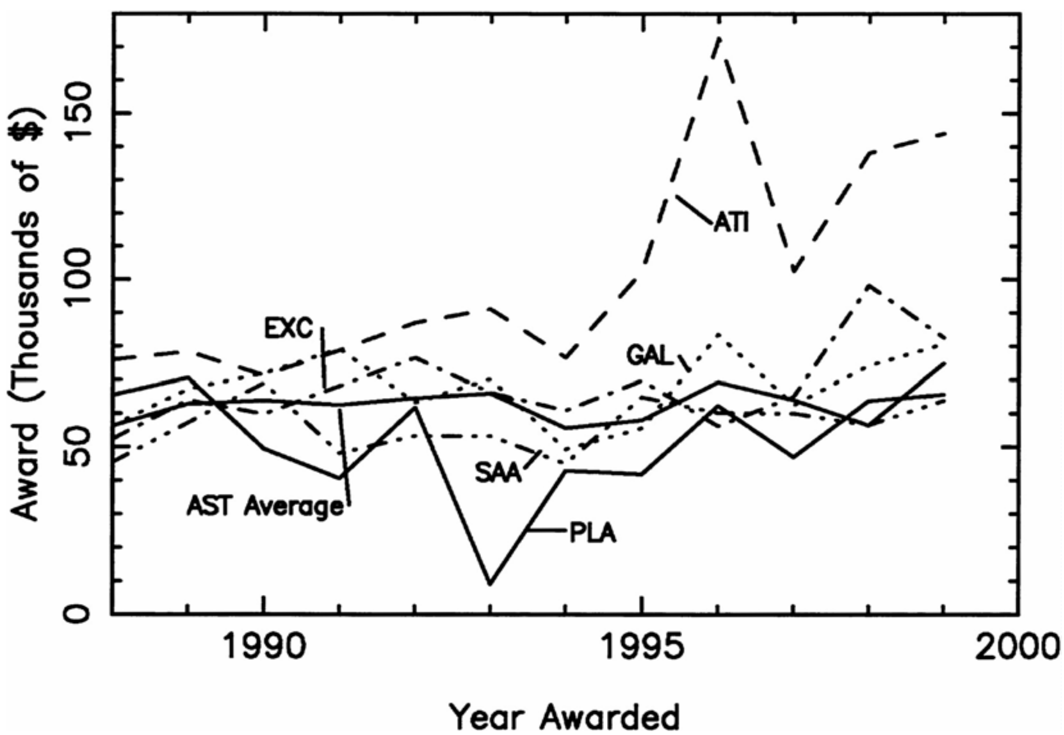

FIGURE 5.7 Median size (annualized) of successful proposals in NSF AST and its major programs. Amounts adjusted to 1997 dollars. SOURCE: NSF Division of Astronomical Sciences.

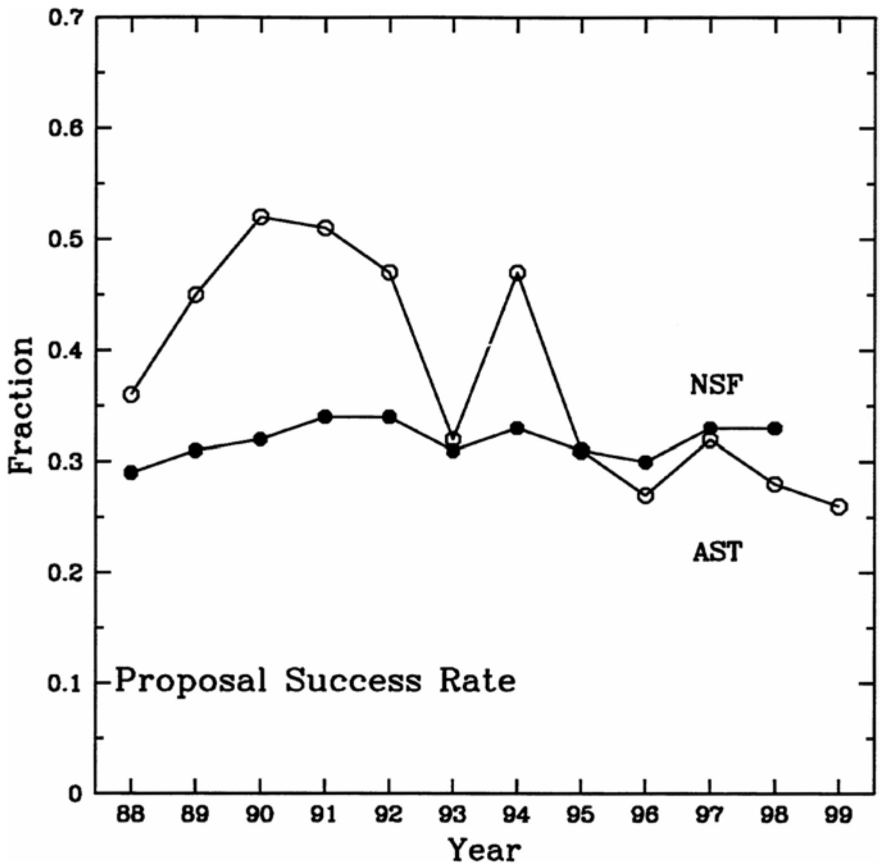

FIGURE 5.8 Fraction of successful proposals in NSF AST (open symbols) compared to the overall success rate for NSF competitive proposals (filled symbols). SOURCE: NSF Division of Astronomical Sciences and NSF Experimental Program to Stimulate Competitive Research (EPSCoR) National Almanac, online database, available at <http://www.ehr.nsf.gov/ehr/epscor/per/start.htm>.

Modest amounts of guest investigator funding are sometimes supplied with grants of observing time at some of the NSF-supported facilities. These typically cover travel and publication costs and are described below in the context of observing time oversubscriptions.

To summarize, NSF support for astronomical research declined by about 10 percent (in inflation-corrected dollars) over the past decade. Approximately one-third of this funding supported individual research grants, with the balance supporting major ground-based facilities. The net result has been an increasing pressure on the grants programs, with oversubscription rates of nearly 4:1 in most programs for grants of $65,000 per year.

5.2 THE NASA R&A BUDGET

A detailed breakdown by field and discipline for NASA grants was difficult to obtain due to changing budgeting procedures. The committee is able to provide a snapshot for one year, 1993, and can reliably describe overall R&A funding as a function of time.

Given the variety of programs offered, the observing programs are considered separately from the rest. The numbers are summarized in Table 5.9, where for the satellites the specific proposal cycle is listed, while for the others (mostly theory) the annualized totals for (often) multiyear grants are provided for 1993. For the satellites, oversubscription by a factor of 2.2 is the average across the board, but there is a clear difference among satellites, with the factor reaching 3.5 for HST. Average grants in the satellite program range from $11,600 (Advanced Satellite for Cosmology and Astrophysics [ASCA]) to $74,000 (HST). Overall, grants averaged $25,900.

The theory and archival data programs typically were oversubscribed by a factor of 2.6, with the Theory Program reaching 3.7 (although these numbers represent reports from different years, as summarized in Table 5.9). Average grants amounted to $74,800 but varied widely, from an average for theory of $130,000 to an average in NASA's Astrophysics Data Program (ADP) of $37,500.

Table 5.10 compares the total funding of NASA R&A and DA programs between 1989 and 1999. The most striking trend is a 50 percent increase in total support over the decade, from about $60 million to $90 million, which can be compared to the NSF total research grants program support of $26.4 million in 1998 (Table 5.3). This comparison perhaps more than any other underscores the increasing dominance of NASA over the past decade. Table 5.7 also shows that a single space mission, Hubble, accounts for more than one-third of all NASA support ($31.6 million), which by itself exceeds the total NSF grants program and also exceeds the total NASA astronomy R&A program. Put another way, the sudden loss of HST funding would have a substantially greater impact on astronomy, in terms of total dollars, than the termination of all NSF grant support for astronomy. The operating Chandra X-ray Observatory and the future SIRTF will also have major impacts on astronomy research funding.

5.2.1 NASA Theory Program

The NASA Theory Program was initiated in 1984 in response to a recommendation of the 1982 decadal survey (National Research Council, *Astronomy and Astrophysics for the 1980's. Volume I: Report of the Astronomy Survey Committee,* National Academy Press, Washington, D.C. 1982) that the federal agencies establish theory programs. The first NASA Research Announcement for theory solicited proposals from theory groups. Funding was provided for three years beginning in 1985, leading to a second announcement in 1987. After the third announcement in 1990, there were more individual investigators in the program. During 1993 and 1994 there was a gap in the program. The program resumed in 1994 with some changes: it became an annual rather than a triennial program, and theory components of three wavelength-specific programs (high energy, UV/optical, and IR) were folded into the Astrophysical Theory Program (ATP). The grants moved from these other programs were generally small. In 1997, the theory component of the cosmic ray program became part of the ATP. This program has become a major source of funding for theorists; it rivals the funding for theorists provided by the NSF Astronomy Division.

TABLE 5.9 NASA Grants–FY 1993 Award Snapshot

	Proposals	Grants	Funding Awarded (dollars)
Observing Programs			
ASCA Cycle 1	248	70	1,021,863
EUVE Cycle 1	141	81	2,267,878
CGRO Cycle 3	251	149	4,645,683
HST Cycle 2	427	123	9,104,225
IUE Cycle 16	242	128	143,000
ROSAT Cycle 4	371	231	3,697,373
	1,680	782	20,880,022
Non-observing Programs (Multiyear)			
ADP FY 1993		101	3,787,700
LTSA FY 1993		57	6,215,563
Theory FY 1993		33	4,296,406
		191	14,299,669
Grand Total		997	35,179,691

NOTES: Acronyms are defined in Appendix H. Number of investigators listed on proposals: 577 principal investigators; 1,307 coinvestigators (1,524 distinct persons).

TABLE 5.10 Funding of NASA's R&A and DA Programs in Millions of 1997 Dollars, FY 1989 and FY 1999

	FY 1989		FY 1999
MO&DA Program			
HST DA	12.3	HST DA	31.6
IR/radio	5.4	CGRO MO&DA	1.4
UV/optical	4.3	Other missions	11.2
High energy	2.9	Multidisciplinary programs	14.8
Miscellaneous(LTS A, data)	5.4		
	30.3		59.0
R&A Program			
UV/optical	8.3	UV/optical	9.0
IR/radio	3.9	IR/radio	6.6
High energy	10.3	High energy	9.5
ATP	3.6	ATP	6.2
Airborne	2.5	Airborne	`
	28.6		31.3
Total	58.9		90.3

NOTE: Acronyms are defined in Appendix H.

The funding history of the Theory Program is shown in Table 5.11 and Table 5.12. Table 5.11 shows the funding history of the Theory Program alone. There was an increment in the funding in 1994 to take into account the grants moved from other NASA programs. However, this funding increment does not appear to have been sustained in subsequent years. As measured by oversubscription by number, there has been a steady erosion of the success rate of the program. Table 5.12 gives the integrated theory funding, including funding for theoretical projects in other NASA R&A programs. In looking at averages in two- to three-year intervals to smooth year-to-year discontinuities (since not all programs are competed every year), there has been a decline of about 20 percent in NASA funding for theoretical astrophysics since the beginning of the decade.

TABLE 5.11 NASA Theory Program Funding History, 1987 to 1997

Year	No. of Proposals		Total Budget Requested per Year (thousands of dollars)	Total Budget Approved per Year (thousands of current dollars)	Oversubscription		Total Budget Approved per Year (thousands of 1997 dollars)
	Requested	Accepted			By No.	By Funds	
1987	45	15		2,100	3.0		2,846
1990	118	33	15,233	3,959	3.6	3.8	4,764
1994	212	58	22,600	5,400	3.7	4.2	5,794
1995	180	45	17,700	3,000	4.0	5.9	3,138
1996	137	32	17,631	2,421	4.3	7.3	2,475
1997	179	37	16,054	3,065	4.8	5.2	3,065

TABLE 5.12 Theory Funding (millions of dollars) at NASA, Integrated Over All Programs, 1987 to 1999

Year	Total Budget	1997 Dollars
1987	5.10	6.90
1988	5.20	6.80
1989	5.30	6.65
1990	6.96	8.37
1991	7.05	8.16
1992	6.21	6.49
1993	4.89	5.36
1994	4.59	4.92
1995	5.95	6.22
1996	6.17	6.30
1997	6.49	6.49
1998	5.89	5.78
1999	6.39	6.14

5.3 FACILITIES OVERSUBSCRIPTION

This section describes the facilities that are available to the astronomical community through public funding from NSF or NASA. The list of facilities is limited to those that run periodic solicitations for proposals (i.e., NASA principal investigator (PI) missions are not included except in cases where some of the observing time is distributed through an open guest observer (GO) program). The value of the resources available is assessed in terms of two quantities, observing time and funding for support. For observing time, the committee discusses the amount of time available for U.S. astronomers and the typical oversubscription rates. For the funding for support, it discusses the specific items supported (e.g., travel, page charges, summer salary) and the average and total funds distributed. For funding, the discussion is limited to programs specifically tied to successful proposals for observing time or to GO proposals.

5.3.1 NSF Facilities

The NSF's Division of Astronomical Sciences operates three centers, the National Optical Astronomy Observatories, the National Radio Astronomy Observatory, and the National Astronomy and Ionosphere Center. In addition, the U.S. share of the international Gemini telescopes will be available through NOAO. The NSF also provides some operating funds for four private radio observatories: Owens Valley Radio Observatory, Caltech Submillimeter Observatory, Five College Radio Astronomy Observatory, and the Berkeley-Illinois-Maryland Array.

National Optical Astronomy Observatories

NOAO operates telescopes at three sites: Kitt Peak, near Tucson, Arizona; Cerro Tololo, near La Serena, Chile; and Sacramento Peak, near Cloudcroft, New Mexico. The Sacramento Peak telescopes and two of the Kitt Peak telescopes are solar facilities; the Cerro Tololo telescopes and the remaining Kitt Peak telescopes are nighttime facilities.

The nighttime facilities include two 4.0-meter general-purpose OIR telescopes, two medium-size (2.1-meter and 1.5-meter) telescopes, and two 0.9-meter telescopes. In addition, there are several shared facilities on these sites. These include the 3.5-meter WIYN telescope (40 percent of the time is available generally to the astronomical community), the 0.6-meter Curtis Schmidt telescope (66 percent of the time is available), the 1.0-meter YALO (Yale, Association of Universities for Research in Astronomy [AURA], University of Lisbon, and Ohio State) telescope (10 percent of the time is available), and the 4-meter SOAR telescope (project currently in design phase; 30 percent of the time will be available to U.S. astronomers). For all the telescopes at Cerro Tololo, 10 percent of the time is guaranteed to proposers from Chilean institutions.

The NSF-supported facilities in Chile and Arizona represent the main access to optical facilities for the average U.S. astronomer. Over the past decade, smaller telescopes at both locations have been closed and new, larger (notably the WIYN 3.5-meter in Arizona) facilities opened. Oversubscription is a useful gauge of proposal and observing time pressure for this period.

Approximate average oversubscription rates are 2 to 3 for the 3.5- and 4.0-meter telescopes in recent years, and 1.5 to 2 for the medium-size telescopes. Oversubscription is a strong function of instrumental availability, lunar phase, and time of year. Time is allocated on a semiannual basis, with success rates published on a consistent and systematic basis.

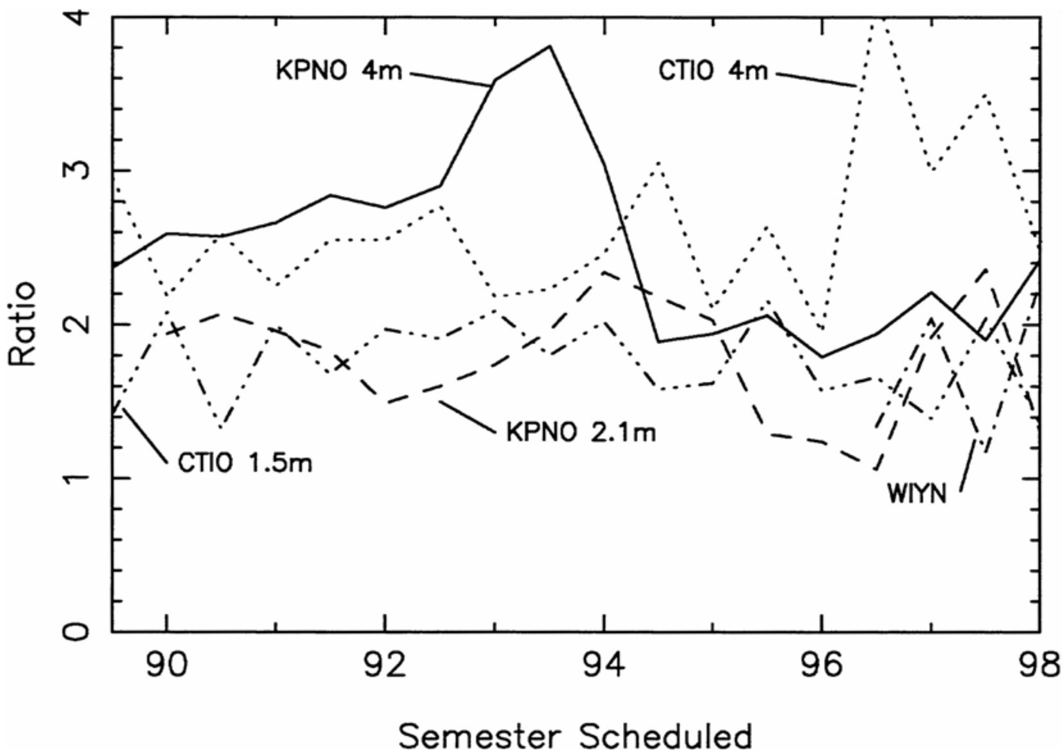

FIGURE 5.9 Oversubscription for NOAO facilities.

Figure 5.9 shows oversubscription rates in terms of time requested versus time available, over the past decade. The demand for the large telescopes shows structure, mostly associated with the introduction of new instruments and the fact that the WIYN telescope is only now in full operation. As illustrated, there has been little reduction in pressure for observing time, even with the increase in aperture-hours. The smaller telescopes are routinely oversubscribed by factors of 1.5 to 2, whereas the large instruments seldom have oversubscription by less than a factor of 2. Optical ground-based facilities available to U.S. astronomers are under continuing heavy demand.

NOAO also provides access to a number of other nighttime facilities through various NSF programs. The U.S. community will have access to 47.6 percent of the time on the two Gemini 8.0-meter telescopes, becoming available in mid-2000 (Gemini-North) and mid-2001 (Gemini-South). Through the NSF facility instrumentation program, approximately 7 percent of the time on the Hobby-Eberly telescope and 7 percent of the time on the upgraded (6.5-meter) Multiple Mirror Telescope (MMT) will be available to the community through NOAO for a period of six years beginning in 1999.

The solar facilities include three telescopes at Sacramento Peak, New Mexico, and three telescopes at Kitt Peak, Arizona. Solar telescopes are run in a somewhat different manner from nighttime telescopes, with some fraction of the time used for synoptic observations carried out by the observatory staff. In the remaining time, visitors use the telescope with their own instrumentation or with observatory instrumentation. A recent compilation of user statistics states that over the 3.75 years from October 1, 1993, through June 30, 1997, 99,176 hours of observing were scheduled on the six facilities. This included 851 separate observing runs representing 343 unique science projects and serving a total of 299 individual users (not counting National Solar Observatory (NSO) staff scientists). For the three most popular facilities, the McMath-Pierce Telescope, the Sacramento Peak Vacuum Tower Telescope, and the Evans Facility, the visitor use fractions were about 0.7, 0.5, and 0.3, respectively.

In the past, NOAO provided travel funds and page charge support for observers, but these were discontinued more than ten years ago. Currently, NOAO travel support is limited to graduate students working on Ph.D. theses. There is no publication support. NOAO administers an NSF fund that supports travel by U.S. astronomers to foreign observatories. This fund totals about $30,000 per year.

National Radio Astronomy Observatory

NRAO operates three facilities, the Very Large Array (VLA) near Socorro, New Mexico; the Very Long Baseline Array; and the 12-meter telescope on Kitt Peak near Tucson, Arizona. In addition, the 100-meter Green Bank Telescope will begin operation in 2000. All of the time on these facilities is available to the astronomical community through a peer-review process.

The VLA consists of 27 25-meter telescopes in a Y-shaped array, with a maximum dimension of 36 km. It operates at wavelengths from 0.7 to 90 cm. The oversubscription of the VLA is typically in the range of a factor of 2 to 3. Over the two (four-month) cycles in 1998, the VLA time requested was slightly more than twice the time allocated, and slightly less than two-thirds of observing proposals were accepted.

The VLBA is an array of 25-meter telescopes at ten sites extending over a maximum baseline of 5,000 miles. It can be used at wavelengths from 0.7 to 90 cm. The VLBA is typically oversubscribed by a factor of 2. Over two (four-month) cycles in 1998, the VLBA time requested was about 1.7 times the amount allocated, and about three-quarters of observing proposals were accepted.

The 12-meter telescope at Kitt Peak is a millimeter-wave telescope operating in all atmospheric windows from 68 to 300 GHz. It is typically oversubscribed by a factor of 1.5. NRAO pays 50 percent of page charges for papers that substantially incorporate original data from NRAO telescopes. NRAO supports travel to make observations or reduce data at NRAO facilities—one trip of each type per program.

National Astronomy and Ionospheric Center

NAIC operates the 305-meter radio telescope near Arecibo, Puerto Rico, which is the primary instrument for radio and radar astronomy as well as ionospheric studies. It has just resumed partial operations after a nearly three-year shutdown for a major upgrade, which included a substantially improved groundscreen and a Gregorian feed system that improves sensitivity and frequency range. Before the upgrade, proposals were accepted at any time and worthy proposals were kept in the queue until completed. Since the upgrade, a semester-based proposal cycle has been instituted, but the telescope has not been in full operation long enough to judge the proposal pressure. Preliminary numbers for the limited access time starting on February 1, 1999, show, even with only the longer-wavelength receivers available, oversubscription by a factor of at least 1.7.

Before the upgrade, about 80 percent of the schedulable time was used for radio astronomy, 3 percent for radar astronomy, and 17 percent for atmospheric research.

University-owned Radio Observatories

The NSF provides a fraction of the funds needed to operate four university-owned radio observatories: OVRO, CSO, FCRAO, and BIMA.

OVRO is not mandated to give time to external proposers by its agreement with the NSF but gives on average about 50 percent of its observing time to external (non-Caltech) proposers. The typical oversubscription factor is about 2 for proposals to work at 3 mm and 4 to 5 for proposals to work at

1 mm. OVRO supplies some funding for external observers on an informal basis to cover lodging and food at the observatory and, occasionally, for data reduction trips. About $10,000 per year is provided in this way.

CSO awards 50 percent (by agreement with the NSF) of its time to external proposers. The oversubscription factor is about 2. Funding support provided to external observers includes paying for accommodations at the site (Mauna Kea) and limited travel. The total value of the funding supplied to external observers is about $75,000 per year.

The oversubscription for FCRAO and BIMA is not considered in this report.

5.3.2 NASA Ground-based Facilities

NASA provides funding to supply U.S. astronomers with a number of different types of observational capabilities. These range from ground-based facilities such as the Infrared Telescope Facility (IRTF; mostly NASA supported and operated through a contract with the University of Hawaii) and the Keck telescopes (NASA Planetary, a one-sixth partner), to space missions, many of which have GO programs. NASA also supports programs such as the HST archive and the Astrophysics Data Program that provide funding to analyze and interpret data previously obtained through either GO or PI observations.

The IRTF is a 3.0-meter telescope on Mauna Kea, Hawaii. NASA funds its operations through a contract with the University of Hawaii. Facility instrumentation comes from NSF funding. Seventy-five percent of the time on the IRTF is available to the community, and half of this must be used for solar system research. Oversubscription by a factor of 2 for solar system time and 3 to 3.5 for non-solar system time is typical. IRTF pays for accommodations and meals for visiting observers and up to 50 percent of the page charges for papers presenting IRTF data.

NASA has bought one-sixth of the time on the two Keck 10-meter telescopes on Mauna Kea. This time is available to the community but is limited to searches for extrasolar planets, studies of the origin and nature of planetary systems, and investigations of our own solar system. The typical oversubscription rate on this time is 2 to 2.5. This program does not make any funding available to proposers.

NASA funds a number of space missions with GO programs. These include both “Great Observatory” class missions (HST, AXAF/Chandra, CGRO, and SIRTF) and more modest Explorer-class missions, some of which have limited GO programs. The smaller missions included in this report are Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA), the Extreme Ultraviolet Explorer (EUVE), ROSAT, the Rossi X-ray Timing Experiment (RXTE), the European Infrared Space Observatory (ISO), FUSE, and SOFIA.

5.3.3 NASA Missions with Guest Observer Programs

Hubble Space Telescope

The Hubble Space Telescope GO program is now in its seventh cycle. Calls for proposals are issued approximately once per year. Oversubscription has averaged about a factor of 3 for the past three cycles, but it has ranged from 2.1 to 4.8 during this time. Estimates are somewhat complicated. Time is given out in “cycles” that do not in general coincide with an annual cycle. Comparisons are further complicated by the initial mirror problems, corrected in time for Cycle 4 (1994) but involving additional lost orbits. More recently there were problems associated with the reduced lifetime of the Near Infrared Camera and Multi Object Spectrograph (NICMOS) cryogens and the subsequent readvertisement for proposals specifically for this instrument.

Figure 5.10 (plotted as though cycles corresponded exactly to years) shows the trends since 1993 (Cycle 2) in oversubscription both for proposals and for observing time (orbits). Oversubscription during Cycles 2 and 3 was high, about a factor of 4. However, with the focus problems, each successful program in general has required extra orbits; the number of accepted programs has thereby been reduced, and the number of orbits scheduled per proposal has increased.

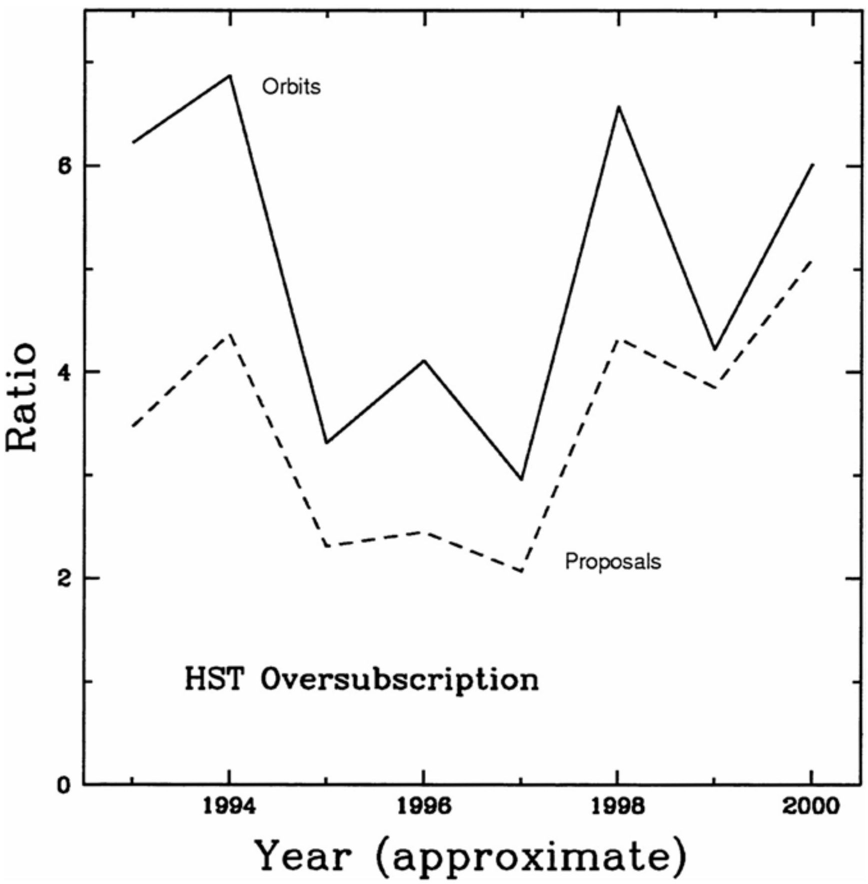

FIGURE 5.10 Oversubscription on proposals and observing time for HST.

After the servicing mission, Cycles 4, 5, and 6 show the effects of the greatly improved throughput, with proposal oversubscription dropping to a factor of approximately 2.5. Cycle 7, anticipating the NICMOS and Space Telescope Imaging Spectrometer (STIS) instruments, showed proposals peaking at about 1,300, albeit for a period in excess of a year; proposal oversubscription rising to a factor of 4.3; and the orbits requested exceeding those available by more than a factor of 6. HST remains heavily oversubscribed.

Chandra

The recent delay of the AXAF/Chandra launch highlights one of the problems faced by the research community. It is estimated that delay of the launch from fall 1998 to summer 1999 cost NASA approximately an additional $40 million. This funding is not currently in the NASA hardware or MO&DA budgets. NASA has "borrowed" the required extra funding over and above the existing small contingency to be paid back from future AXAF/Chandra operations and data analysis funds, including guest observer funding. Unless other funding is made available, NASA's current recovery plan as described to the committee by A. Bunner (November 10, 1998) calls for a decrease of 10 to 20 percent in basic research support over the first five years of operations, a substantial tax on individual investigators.

Compton Gamma Ray Observatory

The Compton Gamma Ray Observatory was launched in April 1991. Cycle 8 of the GO program began at the start of 1999. CGRO has four instruments, BATSE (Burst and Transient Source Experiment), EGRET (Energetic Gamma Ray Experiment Telescope), OSSE (Oriented Scintillation Spectrometer Experiment), and COMPTEL (Imaging Compton Telescope). The GO program is open to the international community with no preallocations. Oversubscription is about a factor of 4 for the three instruments that make pointed observations and about 5 for BATSE, which is an all-sky monitor. The average GO grant is currently about $11,000, a decrease from about $50,000 in the early cycles. Grant funds go mostly for salaries and for support of postdoctoral fellows and graduate students. Travel, computer equipment, and page charges are all allowed.

Far Ultraviolet Spectrographic Explorer

The Far Ultraviolet Spectrographic Explorer mission was launched on June 24, 1999. FUSE will provide a high-resolution (R = 30,000) ultraviolet spectrographic capability over the wavelength range from 905 to 1187 Å. The primary science goals include (1) a study of the deuterium-hydrogen (D/H) ratio and its dependence on the chemical evolution of the interstellar gas in the Milky Way and intergalactic gas in the low-redshift universe and (2) a study of the origins and properties of hot interstellar gas in the Milky Way and Magellanic Clouds as traced through O VI (O^{+6}) absorption and emission. The FUSE program experienced two launch delays. The most recent delay was due to defective gyroscopes. If the full cost implications of the delays are passed on to the FUSE mission operations and scientific data analysis program, the impact on the ability of the PI team and FUSE guest observers to pursue the science goals of the mission will be substantial.

Kuiper Airborne Observatory and Stratospheric Observatory for Infrared Astronomy

Airborne astronomy has been a significant part of infrared astronomical research for the last 30 years. For much of the last decade, the Kuiper Airborne Observatory (KAO), a 0.9-meter IR telescope mounted on a C141 aircraft, was managed by Ames Research Center. For 1986 and 1989 through 1995, the funding in 1997 dollars was $8.3 million ($3.5 million), $10.1 million ($3.7 million), $10.6 million ($3.7 million), $11.1 million ($3.6 million), $11.3 million ($3.7 million), $11.7 million ($3.6 million), $11.2 million ($3.6 M), and $10.6 million ($4 million), where the number in parentheses is the amount for user grants and the first number is everything else (e.g., operations, aircraft maintenance).

There were about 12 to 14 PI teams at any one time, including on average 5 to 10 scientists per team (counting graduate students and postdoctoral fellows); thus, there were about 100 active scientists in any given year. There were on the order of 25 to 30 guest investigator programs with two to three scientists per team, again including graduate students and postdocs. Thus, approximately 175 scientists were using the KAO or associated with it in any year. In addition, there were about 70 support personnel. The fraction of solar system observations ranged from a high of about 30 percent to a low of about 15 percent toward the end of the program, with the remainder being galactic or extragalactic observations. Funding during the last year of KAO operations in 1995 included approximately $2 million for instruments, $1.2 million for observations and data analysis for galactic studies of the ISM, $0.3 million for extragalactic studies, and $0.5 million for other astronomical research such as solar system studies.

With the decommisioning of the KAO in late 1995, most of the funding for airborne work is now in the SOFIA budget. SOFIA is a 2.5-meter telescope that will operate in a modified Boeing 747SP. Development of SOFIA is under way and should be completed by 2001. Roughly $40 million to $50 million was spent in development in calendar year 1997. The budget for the four-year development is about $55 million per year. Of this, about $4.5 million per year has been set aside for science instrument development. The first such awards were not made until September 1996, so only about $2 million was spent in FY 1997. A total of three facility instruments and four PI-class instruments are currently under development. There is also a near-IR camera for checkout of the optical performance of the telescope that will be useful as an eighth science instrument at first light. Observations are to start in early 2002. SOFIA will be accessible to a much wider range of astronomers than was KAO. The scientific usage is expected to be roughly 50 percent for star formation studies, 30 percent for extragalactic astronomy and cosmology, 10 percent for planetary science, and 10 percent for other studies. The data are to be archived for the community.

5.3.4 Instrumentation for Ground-based Telescopes

Over the next several years, U.S. ground-based optical and infrared astronomers will see a very large increase in the collecting area of ground-based optical and IR telescopes, with apertures exceeding 5 meters (see Table 5.13). These telescopes will have a profound effect on the ability of ground-based astronomers to pursue a wide range of fundamental astronomical problems. In fact, counting telescopes of diameter >2 meters, in 1990 the total collecting area available to U.S. astronomers was only about 110 square meters. By 2003, this number will have risen to nearly 600 square meters, more than a factor-of-5 increase (see Table 2 of the 1995 NRC report *A Strategy for Ground-Based Optical and Infrared Astronomy* and the partial update for large telescopes given in Table 5.13).

Much of the large increase in telescope collecting area has and will come as the result of support from private foundations and both state and private U.S. academic institutions. Private money and academic institution money will also help support the operation of many of these major astronomical facilities. However, to realize the full potential of this large gain in light-collecting ability, it is necessary to instrument these new telescopes properly.

Although some funds to instrument large telescopes have recently come from NASA, the NSF will have to take on the primary responsibility for creating a vigorous optical and infrared instrumentation program for these new facilities as discussed in *A Strategy for Ground-Based Optical and Infrared Astronomy.* In that strategy a vigorous facility instrumentation program was recommended to the NSF. This program was intended for the independent observatories with large telescopes. Instrumentation grants are awarded on the basis of scientific merit but are tied to the provision of access to the astronomical community at large. The committee recently reviewed the cost-sharing and community access aspects of the above report and agreed that this important element of the program should be continued, but with a modification in the cost-sharing formula such that the NSF would have more flexibility in trading facility instrument funds for telescope access. (See "On the National Science Foundation's Revised Facility Instrumentation Program," June 2, 1999, provided to AURA and NSF.) This modified payback scheme would allow the NSF to more fairly recognize and award independent observatories for their successes in obtaining private and state funds for construction and operation.

TABLE 5.13 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]
Keck I	100	1993	10	94	13.5
Keck II	100	1996	10	78	28.1
HET	90	1998	9	17	3.6
MMT[b]	100	2000	6.5	23	26
Gemini-North[c]	52	1999	8	86	11.2
Gemini-South[c]	42	2001	8	86	7.6
Magellan I	90	2000	6.5	38	9
Magellan II	90	2002	6.5	36	9
LBT	50	2002	2×8.4	77	13
SALT	12	2002	10	17	

NOTE: Acronyms are defined in Appendix H.

[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.

6

Discussion

Astronomy is now in a golden age, with scientifically important and newsworthy discoveries from innovative and new facilities occurring almost every week. There is extremely strong public interest in NASA's Origins Program and in astronomical research in general. The amount of collecting area on large telescopes available to the U.S. community tripled in the last decade of the 20th century, and despite significant investments in astronomy on the part of the European Southern Observatory (ESO) and Japan, the United States still comfortably leads the field. More is yet to come with the commissioning of another five to six new large ground-based telescopes, the recent launches of Chandra and FUSE, and early in this century, the launch of SIRTF and later in the decade NASA's Next Generation Space Telescope (NGST).

The charge to the committee encompasses three major questions:

1. What have the trends been in basic research support in astronomy, for example, grant funding, growth in number of astronomers, proposal success rate, average grant size and duration, publication support citations, and other measures of research vitality?
2. What are the trends in federally funded basic research support for astronomy, including support for theoretical astrophysics, and how is this support aligned with the availability of major observational facilities (including both ground-based and space-based observatories)?
3. How vulnerable is the astronomical research community to unexpected setbacks, such as a catastrophic failure of the Hubble Space Telescope?

The committee was able to collect data on demographics, funding, and scientific output as measured by publications that bear directly on these three issues. It found generally that NASA funding overall remains healthy, providing the backbone of support in many critical fields. The NASA Long Term Space Astrophysics (LTSA) and Theory programs have provided a stable foundation of long-term astrophysics-driven support, to partly balance the mission-oriented approach of most NASA programs.

Demographic trends in astronomy remain very healthy in comparison with those in many other physical sciences. There is a steady infusion of new Ph.D.s, and graduate enrollments remain strong in the face of strong declines in physics.

6.1 BALANCE AMONG AGENCIES

Over the past two decades there has been a dramatic shift in the way astronomical research has been supported. At the start of the 1980s, NSF provided 60 percent of the federal support for individual research grants. By the end of the 1990s, NASA was providing 72 percent of the support for individual grants. Despite this significant funding shift toward a basically mission-oriented agency, the committee was unable to detect any dramatic changes in the distribution of the subfields of astronomy. Generally, the fraction of astronomers working in different subfields has not changed substantially, the fraction of papers published in each subfield has not changed dramatically, and the fraction of astronomers employed at universities, colleges, government labs, and FFRDCs has not changed significantly. The committee was surprised by the tremendous continuity of the field.

Over the past 12 years there has been a dramatic growth in the fraction of journal publications funded by foreign agencies and written by foreign authors. This growth parallels the flourishing of Japanese and European astronomy. The Europeans and the Japanese have built several major observatories, including the European Very Large Telescope (VLT) and Subaru, and have launched several cutting-edge satellites. While American astronomy benefits from collaboration on foreign-led joint missions such as ROSAT, ASCA, and ISO, the U.S. effort will have to keep pace with this overseas growth if the United States is to maintain our world leadership role in astronomy.

6.2 GROUND-BASED OPTICAL FACILITIES

The construction of large ground-based optical telescopes, primarily via private funds, has resulted in a large gap in the funding of the design, development, operation, and construction of instrumentation for these facilities. The 1995 NRC report *A Strategy for Ground-Based Optical and Infrared Astronomy* recommended a vigorous facility instrumentation program. This need continues.

While NASA has always funded the analysis and interpretation of data obtained from space, NSF has not provided the necessary funds for this activity for ground-based astronomy. The fraction of NSF proposals that are funded has been dropping steadily and is now near 28 percent. Thus, while ground-based astronomers have excellent and increasing access to new telescopes, they often lack the funds for computers, travel, theoretical precursor and follow-on studies, and postdoctoral fellows to take proper advantage of this access. Increases in NASA observing grants have taken up some of the shortfall for general support but only indirectly address the problem. One possible solution is to adopt an approach similar to NASA's and identify in advance of the construction of telescopes and instruments the resources necessary to utilize them fully, including funds for theory and facility instruments. The recent wave of construction of new large telescopes summarized in Table 5.13 has been financed largely by private donations. Although NSF has no specific obligation to support the instrumentation of these new private facilities, the committee calls attention to the vulnerability of the U.S. research effort and leadership in ground-based astronomy if adequate funding for these instruments, whatever the source, is not raised and reemphasizes the findings of the NRC report *A Strategy for Ground-Based Optical and Infrared Astronomy.*

6.3 VULNERABILITIES

The U.S. program in astronomy and astrophysics would be severely affected by the catastrophic failure of one of its premier observational facilities such as HST or Chandra. The consequences of a failure of HST, the current worst-case scenario in astronomy, are examined briefly here, and similar ramifications of the failure of Chandra are noted.

Construction of HST began in 1977. Although it has been refurbished three times since being placed in orbit in 1990, many of its basic components date to the late 1970s. As HST continues to age, the chances for catastrophic failure increase. The recent failure of one of HST's remaining gyroscopes is an example. Each HST space shuttle servicing mission is a risky operation. Although we all hope that HST can be operated to 2010, we must be prepared for an earlier failure.

Premature failure of the HST would present a very major setback to the United States and international programs in astronomy and astrophysics. The research community would lose an extremely important research tool, and NASA would lose a mission that has played a major role in convincing the public that space research is interesting and exciting. In addition to these major losses, the funding implications for the U.S. astronomical community would be significant. The HST project provides guest observer funding to the astronomical community, which has averaged approximately $20 million per year from 1995 to 1998. Approximately another $10 million is provided to the HST guaranteed time observers (GTOs), who receive observing time for their efforts to build the HST focal plane instruments, and to the Hubble fellowship program. As can be seen from the preceding sections, HST GO and GTO funding currently represents approximately 30 percent of the total direct grant funding to the U.S. astronomical community. Much of this money funds the salaries of Ph.D. astronomers, graduate students, and institutional technical support staff. The HST program supports an average of 40 Hubble fellows per year and maintains the Space Telescope Science Institute in Baltimore, Maryland. The STScI has a staff of approximately 60 astronomers and 180 technical support personnel. A similar-sized staff for HST operations, although with fewer scientists, is at GSFC. The STScI is the site of the NASA UV/Optical data archive and has recently been designated by NASA as the supporting institute for the NGST. If HST were to fail, the rapid reduction of about 30 percent of U.S. small-grant funding, the loss of the Hubble fellowship program, and likely staff reductions at STScI and GSFC would severely damage the U.S. astronomical research community.

6.4 THE NATIONAL SCIENCE FOUNDATION

Despite the tremendous growth of astronomical capabilities and the enormous public interest in astronomy, the fraction of NSF funding for astronomy has been flat. As a fraction of the total NSF budget, astronomy has declined slightly from about 6 percent in the 1970s to about 5 percent today. This funding must also support a growing number of new subfields (e.g., submillimeter and neutrino astronomy). NSF funding for astronomy just about kept pace with inflation despite the growth of the community. Although NASA funding has increased and astronomy as a whole appears to be robust, the subfields in which NASA support is generally not available do show some decline (e.g., the fraction of active U.S. astronomers who are radio astronomers).

6.5 RECORD KEEPING

In preparing this report, one final issue became clear to the committee. This study, as well as the recent Space Studies Board (SSB) study of the NASA R&A program (*Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis,* National Academy Press, Washington, D.C., 1998), was somewhat hampered by the difficulty in obtaining adequate information from the agencies. This problem is manifested in several ways. First, records often have not been kept in a manner that would allow easy access. Although the “top-down” records of agency funding are available from various statistical abstracts of federal funding, records broken down by discipline or even records of individual grants are difficult to obtain. This is often due to the fact that one agency (NASA in particular) may fund investigators and developers in many different ways: direct contracts and grants from the agency, grants and contracts administered by NASA centers, and grants administered by affiliated agencies and subcontractors such as the Jet Propulsion Laboratory (JPL) and STScI. Each program has separate record-keeping procedures and formats, and there is no central depository for information agencywide.

A related problem is the changing of accounting procedures and practices. Over the period considered in this study (1987-1997), NASA restructuring has resulted in similar programs falling into two or even three different program areas or offices. There is no uniform procedure for classifying grants and contracts, even in agencies where record keeping for individual grants has been relatively good. To be fair, some of the perceived problem is the result of improvements in computer and database technology—there were slightly higher standards for accountability and data tracking in 1998 than there were in 1985. However, the committee believes that understanding long-term trends in support is beneficial to the agencies and the Congress and that this area needs improvement in the development of a common classification scheme for contracts and grants, in the centralized collection of such information when that has not been done, and in the inclusion of data from at least eight years ago in the agencies' funding databases. A key part of such a program would be to ensure that changes in agency management structure do not inhibit the ability to track funding for subdisciplines in astronomy and other fields.

7

Findings

In gathering data on research trends, the Committee on Astronomy and Astrophysics found U.S. astronomy to be in generally good health. The United States still leads the field. New discoveries continue to be made at a quickening pace. Observational capability continues to grow rapidly with the construction and deployment of ground- and space-based instruments of remarkable power.

The principal findings of the committee are as follows:

Finding 1. There has been a dramatic shift in the funding for individual research grants in astronomy, with NSF's share falling from 60 percent at the beginning of the 1980s to 30 percent at the end of the 1990s. NASA's share of the grant funding has risen commensurately.

The continuing growth in funding for the astronomy enterprise in the 1980s and 1990s has been largely the result of the success of the NASA space science program, in particular the launch of NASA's Great Observatories and several midsized facility-class satellites. At the beginning of the 1980s, the NSF provided 60 percent of the federal support for individual research grants. By the end of the 1990s, NASA was providing 72 percent of the support for individual grants. Another important factor in the growth in funding for the astronomy enterprise has been a large influx of private funding for the construction of ground-based telescopes.

Finding 2. The overall level of federal support for astronomy remains strong, but shifts in funding patterns, with NSF supplying a declining percentage of grant funding relative to NASA, have the potential to create imbalances that could be detrimental to the overall health of the field. For example, funding for broad-based astrophysical theory has not kept pace with the growth in funding for astronomical research overall.

With NSF's relative role in astronomy continuing to shrink, the subfields that depend primarily on NSF funding are vulnerable. The running three-year average annual budget of NSF's Division of Astronomical Sciences declined (by about 5 percent) from 1990 to 1999. This decline affects both the grants programs, since the number of astronomers increased over this 9-year period by 15 percent, and the facilities and instrumentation program. Increases in NASA funding have taken up the shortfall in some areas such as optical and infrared astronomy; however, the shift in balance toward mission-oriented support has created vulnerabilities in subfields for which NASA support is not readily available, such as broad-based theory, computational astrophysics, and radio astronomy, where some erosion in grant funding is already evident. The committee was unable to produce an exhaustive list of vulnerable research areas but suggests that funding balance across subfields of astronomy is an important issue that requires further study.

Finding 3. Although the number, size, and capability of ground-based observing facilities, both public and private, have increased considerably, there has been no commensurate increase in NSF funds for utilizing these facilities (i.e., for instrumentation, individual research grants, or theory).

Rapid growth and change create problems of adjustment. Funding for utilization of both ground-based and space-based astronomical facilities remains an important issue. In some fields of astronomy, support has not been adequate to exploit the dramatic scientific discoveries of the last decade or to pursue the opportunities made available by the explosion in scientific capabilities. For instance, the number and scope of ground-based facilities have grown with the development and construction of large, private and state-funded ground-based telescopes and with NSF initiatives that include the GBT, the Gemini telescopes, the Arecibo telescope upgrade, and ALMA/MMA. Yet funding for instrumentation, theory, and observer grants at NSF has not kept pace with support for construction. Facility instrumentation for major new telescopes is a clear need for the foreseeable future in response to the leaps in technical capabilities and the large increase in telescope collecting area. Training of instrumentalists is also an outstanding need, for both ground-based and space-based facilities.

Finding 4. As a result of NASA's increased role in astronomical research funding, a large portion of the total support is tied to a few flagship space missions.

NASA is a mission agency, and its program is strongly focused on initiating and launching space-based instruments. Funding for operations and research accompanies each mission. This paradigm has been extremely effective in maximizing the scientific return from these missions. However, the worrisome corollary of this arrangement is the potential for premature termination of the research support associated with a mission in the event of a catastrophic mission failure. Although NASA has a strategic planning process that is quite effective in engineering smooth transitions from one mission to another, there appears to be little explicit planning for unexpected or premature mission termination.

In the event of failure of a centerpiece astronomical research mission in space at a time when follow-on missions remain far in the future, there is a potential for a major impact on astronomical research. The impact would follow not only from the loss of a major observational tool, but also from the premature termination of the stream of research data and the flow of funds to analyze the data. Because analyzing the data from such major missions occupies a significant fraction of the astronomy and astrophysics research community, the personnel impact could be substantial, which could in turn dampen the community's ability to help plan for, and utilize, future missions. For example, the HST grants program accounts for roughly 25 percent of all individual investigator funding in astronomy. It supports researchers at all levels, including students and postdoctoral fellows. The additional loss of jobs directly associated with STScI and GSFC resulting from an HST failure would be substantial, not to mention the loss of a primary scientific capability. Recovery of the scientific personnel complement and the nation's astronomical research capability from such a catastrophe would be slow.

Most important is that a significant fraction of the support for the youngest members of the field comes from such missions. The impact on the youngest astronomers, such as those supported by CGRO, Hubble, and Chandra fellowships and those supported by the R&A funds for such missions, would be disproportionately large and would significantly affect the future of the field.

Based on the results of this study, the committee suggests that the following proposition be considered in future assessments of the field: plans for future facility construction, both ground based and space based, should be accompanied by a strategy to accomplish the scientific mission, including provision of instrumentation for ground-based telescopes, support for observations, and funds for the necessary and relevant astrophysical theory. The strategy should include contingencies for ensuring the continuity of research in critical subfields in the event that major facilities are lost or significantly delayed. It should also include sufficient funding for the training of instrumentalists and for the development of new instrumentation for both space- and ground-based observations. It is necessary to balance the spending on hardware and research personnel, and to keep the mix of people suitable to the directions of growth in the field. The overall goal of both NSF and NASA for astronomy must be to maximize the scientific return by making investments in a balanced program.

Better and more stable accounting and record-keeping processes would enable long-term demographic and policy studies and would also facilitate coordinated stewardship of astronomy and astrophysics. NASA and NSF should continue to improve cooperation to ensure that critical areas are not neglected and to maximize the nation's scientific return from areas of overlapping agency interest.

The NRC report *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis* (National Academy Press, Washington, D.C., 1998) highlighted another problem at NASA. NASA currently groups data analysis and missions operations, two very different categories, into a single budget item. Mission operations (MO) involve a team of engineers maintaining and operating a satellite. Data analysis (DA) funds support scientists using the mission data to answer scientific questions. Because the MO and DA numbers are commingled in the NASA budget, the committee found it impossible to track the level of science support at NASA. The committee strongly encourages NASA to separate these two items. Treating the two separately would enable both NASA and outside groups to better evaluate and optimize programs.

One possible path for record keeping might be to use the system described in this report to categorize grants by field and discipline and by the overall categories of instrumentation, technology development, operations, individual investigator research, and construction. Agency databases with annualized grant figures properly categorized not only would help those trying to track changes in the field but also could supply input for broader science policy decision making. In this context, the committee also urges scientific societies to track membership demographics by collecting information directly from their members on discipline, field, and employment status and location.

In compiling the data for this report, the committee came across several areas, such as the study of the Shoemaker-Levy Jupiter collision, in which NASA and NSF cooperated on interesting and significant programs. NASA, DOE, and NSF should continue to improve such cooperation to ensure that critical areas are not neglected and to maximize the nation's scientific return from areas of overlapping agency interest. This includes intra-agency cooperation as well.

APPENDIXES

A

Discipline and Field Categories

Since one of the main requirements of this study was to track the health of the various subfields and subdisciplines in astronomy, it was necessary to define classification categories (see Table A.1). These are of necessity broad and general and have proven to be useful for the committee's studies of grants, publications, and research personnel. “Discipline” refers to the primary activity of a grant, individual investigator, or publication; for example, papers primarily describing new optical observations would be classified as OO, papers describing a purely phenomenological analysis of data would be classified as theory (TH), and so forth. “Field” refers to the area of study, such as the Sun, Earth's planetary system, star formation, cosmology, and so on. A paper on optical observations of the Sun would be classified as OO/SO (solar). Any such analysis of either individuals or grants, and sometimes publications, is at some level subjective since individuals, for example, often work in more than one discipline and in more than one field.

Note that the discipline category observational infrared (OI) covers part of the wavelength region traditionally considered infrared astronomy, 1 to 3 microns. The split was made this way in part to distinguish between observations requiring space or airborne platforms and those usually done from ground-based telescopes and in part because near-IR (NIR) observations and instrumentation are now closer to optical in nature than far-IR (FIR). Even this split is not optimal because longer-wavelength observations can be done from the ground in some transparent bands, and optical and NIR observations are done in space with the HST. Observational radio (OR) also extends to wavelengths as short as 350 microns if done from the ground. Since different people categorized publications and AAS members and since it is generally easier to classify a single publication rather than the body of work that might pertain to an individual, slight differences exist in these classifications. Ground-based NIR-related publications were classified as OO, while space-based NIR-related publications were classified as OI.

TABLE A.1 Disciplines and Fields

Discipline		Field	
OR	Observational radio or SMM	PL	Planetary
OI	Observational IR (3 microns+)	SO	Solar
OO	Observational optical/IR	ST	Stellar
OU	Observational UV	IM	ISM+the Galaxy
OH	Observational HEA	GA	Galaxies+clusters
EP	Experimental particles and fields	AG	Active galactic nuclei
EA	Laboratory strophysics	SF	Star and planet formation
TH	Theory	IN	Instrumentation
AE	Aeronomy or atmospheric science	CO	Cosmology
AM	Amateur or historian	FM	Fundamental experimental
AD	Administration	NA	Not applicable

NOTE: Acronyms are defined in Appendix H.

B

American Astronomical Society Membership

American Astronomical Society (AAS) membership figures (see Table B.1) are from K. Marvel and R. Milkey and are taken from the *Bulletin of the AAS.* There are differences in sampling dates between the 1980s and late 1990s. In the 1980s, the figures refer to membership as of the end of the calendar year; in the late 1990s, the membership was sampled for the June AAS meeting and does not include membership renewals and applications that arrived later in the year. In 1988, the AAS changed its fulfillment system and the numbers are not available. The small increase in membership in 1995 is due in part to a special two-year AAS program, AASTRA, to enroll K-12 science teachers by giving them free or reduced-rate membership. The number of AASTRA members is now essentially zero.

TABLE B.1 American Astronomical Society Membership by Year, 1984 to 1999

Year	Full	Jr.	Total	Month Sampled
1984	2,813	410	4,185	December
1985	2,830	401	4,258	December
1986	2,920	310	4,382	December
1987	2,992	434	4,540	December
1988	—	—	—	
1989	3,263	490	5,175	December
1990	3,414	767	5,710	December
1991	3,715	712	5,900	December
1992	3,812	625	6,050	December
1993	3,901	795	6,318	December
1994	3,849	826	6,269	June
1995	4,097	834	6,566	June
1996	3,940	874	6,657	June
1997	3,807	831	6,610	June
1998	3,840	912	6,701	June
1999	3,986	988	6,971	May 26

Full members of the AAS generally have Ph.D.s. Associate, emeritus, and corporate members are included in the total membership figure. These numbers are slightly different from those in the 1991 Decadal Report because they have not been corrected downward by the estimated fraction of AAS members who are foreign. In the 1991 Decadal Report, the fraction of foreign members was estimated to be approximately 18 percent. In 1998, the fractions of full and total foreign membership were 19 percent and 15 percent, respectively. U.S. membership was determined strictly by country of residence, not by citizenship, because the AAS membership database does not currently contain citizenship information.

The committee reiterates that the more detailed AAS membership breakdown by field and discipline was done for U.S. members only.

Note also that AAS membership varies with time during the year as membership renewals arrive. The bulk of the membership renews by the January 1 start of the membership year; however, new memberships and renewals come in throughout the rest of the year. Until 1993, the membership numbers are those quoted for the end of the year in the Executive Office report for the January meeting. Starting in 1994, membership totals are reported at the June meeting of the society, so some of the decline between 1993 and 1994 represents the reporting date. Almost all members renew by the June meeting.

C

Deflators

TABLE C.1 Deflators Used to Obtain 1997 Dollars

Year	Deflator
1986	0.715
1987	0.738
1988	0.764
1989	0.796
1990	0.831
1991	0.863
1992	0.888
1993	0.911
1994	0.932
1995	0.956
1996	0.978
1997	1.000
1998	1.018 (estimated)
1999	1.039 (estimated)

NOTE: Gross domestic product (GDP) deflators for 1986 to 1995 are from the Council of Economic Advisors and for 1996 to 1999 are from the Office of Management and Budget. These are the factors by which budgetary figures for each year are divided to obtain equivalent 1997 dollars.

D

National Science Foundation Budget Numbers

TABLE D.1 National Science Foundation and Mathematics and Physical Sciences Directorate Budget Numbers in Millions of Real-Year Dollars, 1990 to 1999

Year	Total NSF R&D[a]	Total NSF R&RA[b]	MPS[c]	MPS+MRE[c]
1990	1,729	1,555	514.09	518.50
1991	1,893	1,773	541.63	564.13
1992	1,972	1,871	584.36	622.36
1993	2,014	2,046	585.86	619.93
1994	2,243	2,168	617.88	634.92
1995	2,396	2,281	645.24	771.24
1996	2,391	2,327	660.51	730.51
1997	2,424	2,434	693.45	748.45
1998	2,501	2,572	675.09	713.40
1999	2,714	2,809	706.83	736.67

[a] NSF total R&D funding from AAAS historical data on federal R&D, March 1999, available online at <http://www.aaas.org/spp/dspp/rd/guide.htm >.

[b] NSF total R&RA funding from NSF and R. Konkel; does not include facility construction.

[c] NSF MPS data are from R. Eisenstein and P. McNamara and include science and technology centers' funding. The column labeled MPS (Mathematics and Physical Sciences Directorate, NSF) does not include funding for major research equipment (MRE).

E

Additional Sources of Funding for Astronomy

E.1 RESEARCH FUNDING AT NASA FACILITIES

In addition to the R&A funding discussed in the main body of this report, NASA supports astronomical research at its centers. This support is covered in the overall NASA budget but does not appear either in the Office of Space Science budget or in that subset of the OSS budget associated with R&A, except for grants made to NASA center scientists through the R&A program, scientists supported in part by the MO budget, and funding made available to the centers for technology development. The committee obtained only partial data on NASA astronomy research funding at its centers, in part because astronomy research at the centers is generally not tracked separately.

E.1.1 Ames Research Center

Astronomy and astrophysics are essentially confined to the Planetary Systems Branch and the Astrophysics Branch of the Space Sciences Division at the Ames Research Center. There is also an Astrobiology Branch that obtains funding from NASA grants, but the committee has excluded this from an astronomy classification. The Planetary Branch is composed mostly of theoretical planetary scientists whose primary focus is origins, work that is more focused than the research carried out in this branch earlier in the decade; for example, work on planetary magnetospheres and stellar atmospheres has now essentially been phased out. There are currently 19 scientists in the Planetary Branch with GS 14-15 salaries averaging about $90,000 per year in 1997 dollars. Although slightly higher now, the number of scientific personnel has been 15 ± 2 over most of the past decade. Over the same period, the Astrophysics Branch has had 10 to 12 scientists, many—if not most—being instrumentalists, at GS 14-15 salaries averaging $90,000. For example, personnel in the Astrophysics Branch are currently constructing a facility instrument for SOFIA, and they are designing the telescope aperture door. There are additional support personnel (e.g., one to two secretaries and about three mechanical [shop] technicians plus some technical support) at Moffett Field. The secretaries' and shop technicians' numbers at Moffett have declined over the decade. Most of the technical support in addition to the shop technicians must be bought and paid for with R&A dollars from the grants. The salaries of these support personnel are in the GS 9-12 range. The travel support for all the civil service employees in the Planetary Systems Branch last year was about $120,000.

Aside from the salaries and travel budgets received directly from NASA, all support of science activities in both branches comes from grants supplied by the same NASA research programs that give grants to university PIs. Overhead is extracted from the grants, but it is called a tax. Part of the tax extracted from these grants goes into the Director's Discretionary Fund. Members of the scientific staff have on occasion been invited to write internal proposals to use some of the discretionary funds for science. The outside grants are typically used in the Planetary Branch to fund coinvestigators or postdocs whose official places of employment may be SETI (Search for Extra Terrestrial Intelligence) or one of the local colleges, although they work exclusively at Ames on Ames scientific projects. There are approximately 30 such coinvestigators currently in the Planetary Branch supported on soft money. There has been a steady increase in this type of scientific personnel over the decade.

The postdocs at Ames have numbered between 10 and 20 over the decade, and they have been exclusively NRC fellows, with support funneled through the NRC from NASA. Last year NASA funding evaporated and the NRC fellowship program went bankrupt, but the program has been fully restored this year.

The total amount of funding for astronomical research at Ames in addition to direct grants and contracts is estimated to be about $5 million per year based on the information above and standardized assumptions about the total cost of scientists ($150,000 per year) and postdocs ($80,000 per year), which includes salaries, benefits, and overhead. A significantly larger amount of funding for astronomy at Ames comes through the airborne observatories program. The Kuiper Airborne Observatory and the next-generation airborne observatory (SOFIA) are described in Section 5.3.3 under NASA facilities.

E.1.2 Goddard Institute for Space Studies

Currently there are only two scientists at the Goddard Institute for Space Studies (GISS) involved in astrophysical research, so the federal investment here is less than $0.5 million per year.

E.1.3 Goddard Space Flight Center

Astronomy and astrophysics at GSFC is conducted in the Sciences Directorate, primarily in the Laboratory for High Energy Astrophysics and the Laboratory for Astronomy and Solar Physics. There are other smaller programs in the Laboratory for Extraterrestrial Physics (primarily comets and planetary work) and in Space Science Data Operations. There are approximately 100 civil service Ph.D.s who conduct astronomy and astrophysics research, a number that has been approximately constant for more than a decade, with new hiring balancing attrition. Over the past five years, however, there has been virtually no hiring (although in the past year, seven term appointments have been made that are expected to be converted to ordinary civil service appointments over the next few years). There is a center strategic initiative that, if carried through to fruition, should result in an increase of about 10 percent to the civil service astronomy and astrophysics staff steady state after 2000. Funding for civil service salaries, travel, and overhead comes directly out of NASA funds and is not subject to reprogramming in accordance with the current congressional authorization, although reprogramming is planned in the future.

Expansion (or contraction) of the civil service staff is under the control of GSFC-level management, NASA headquarters, and ultimately, Congress. The primary research areas are (roughly in order of the size of the staff) these:

- High-energy astrophysics (x-ray, gamma-ray, and cosmic-ray astrophysics),
- IR astronomy,
- UV astronomy,
- Planetary research,
- Solar physics, and
- Comets.

In the last 10 years, the IR and high-energy astrophysics programs have increased their civil service staff, the UV and solar physics numbers have decreased, and the planetary and comet programs have remained about the same. The present estimates are that 50 to 75 percent (on average) of civil service time is devoted to programmatic activities and that much less than 50 percent is available for research.

All research funds are competed for in the usual fashion through the peer-review process. Most of this funding is secured from NASA headquarters (NASA civil service employees cannot submit proposals for NSF funding). There is also an internal GSFC Director's Discretionary Fund of about $2.5 million per year, which is available for science and technology proposals that are internally peer reviewed–astronomy and astrophysics typically is awarded about $1 million per year, usually for instrument concepts, with annual funding per proposal at about the $50,000 level.

The other main source of pure research support at GSFC is the NRC fellowship program, which offers about 20 postdoctoral fellowships each year, primarily to new Ph.D.s. These positions are competitive and are reviewed by the NRC. The funding comes primarily from NASA headquarters and is not fungible. The support includes salary, benefits, and a small travel stipend. In general the host laboratory at GSFC is responsible for providing additional support (computers, additional travel, publications charges, etc.), for which research moneys are used.

Since much (but not all) of the GSFC program in engineering, program support, and software activities conducted in the Space Sciences Directorate is in support of the NASA astrophysics program, it is very hard to estimate how much of the additional funds that support program activities should be assigned to the general funding for astrophysics. Significant research is associated with service functions directed by the civil service staff in general areas such as project science support, mission and data operations, data archiving and dissemination, and so forth. Science support contractors generally spend 20 to 25 percent of their time in scientific research of their own, which is usually associated with the mission that they are supporting. Depending on the specific responsibilities that the center undertakes, the science contractor staff has been as large as about 500 at GSFC when COBE, HST, CGRO, SOHO (the Solar Heliospheric Observatory), and others, were all in their operations phases a few years ago. The total number is now less than 200. Aside from these estimates, no attempt has been made to gauge this level of effort. The committee believes that it is accounted for properly in Section 5.2 on the NASA R&A budget.

From the information cited above, a rough estimate of the level of funding for astronomical research at GSFC, in addition to that directly funded from the NASA OSS budget, is approximately $20 million per year, based on standardized assumptions about the total cost of scientists ($150,000 per year) and postdocs ($80,000 per year), which includes salaries, benefits, and overhead.

E.1.4 NASA Jet Propulsion Laboratory

Funding for astronomical research at JPL comes principally through the Research and Technology Objectives and Plans (RTOP) process and thus shows up in the astronomy and astrophysics budgets of the OSS at NASA but not in the NASA R&A budget discussed in this report. A modest amount of funding for astronomical research comes from the JPL Director's Discretionary Fund.

E.1.5 Marshall Space Flight Center

Astronomy and astrophysics research at Marshall Space Flight Center (MSFC) is conducted in the Space Science Department of the Science Directorate. The Space Science Department has a permanent staff of 41, including 24 Ph.D. scientists and 9 master's-level scientists who work in the various astronomy and astrophysics disciplines. The staff has declined by roughly 20 percent over the past decade. To partially offset this decline, four Ph.D. scientists have been hired on temporary appointments (Intergovernmental Personnel Act or term appointments). NASA headquarters has set a limit of 41 full-time equivalents (FTEs) on MSFC's scientific manpower, a total that includes 6 permanent positions in the study of space plasmas plus secretarial support. Funding for civil service salaries, travel, and overhead comes directly out of NASA funds assigned to MSFC and is approximately $4.3 million per year.

The research disciplines supported at MSFC are high-energy astrophysics (cosmic-ray physics, gamma-ray and x-ray astronomy), solar physics, astrobiology, and planetary research. The personnel breakdown by the four disciplines is 19, 12, 1, and 1, respectively. The funds that support research activities, as opposed to civil service manpower costs, are received in the main from NASA headquarters and obtained through the normal competitive process by responding to NRAs and Announcements of Opportunity (AOs). In FY 1999, this amounted to approximately $4 million and is representative of the level of support received for the last five years. Modest support, at the level of $100,000 to $150,000 per year, is also received from MSFC's Director's Discretionary Fund. In addition to NASA support, occasional funding is also received from other agencies of the U.S. government, especially the Departments of Energy, Commerce, and Defense. Over the long term this has averaged about $100,000 per year.

Another important source of support for astronomy and astrophysics at MSFC is the NRC fellowship program. The program is funded by NASA headquarters, which has allocated MSFC about 10 postdoctoral positions per year. The financial benefit of this program is estimated at $700,000 per year.

In summary, the level of funding for astronomical research at MSFC from all sources is approximately $9.25 million per year, which supports a scientific work force in astronomy and astrophysics of approximately 70 to 80 individuals. Some of the scientists employed by the University of Alabama in Huntsville receive partial support from MSFC.

E.1.6 Space Telescope Science Institute

Research funding at STScI comes through a combination of direct salary support for the scientific staff and a small (approximately $0.5 million per year) Director's Discretionary Fund, which is a negotiated part of the overhead on the STScI operations contract. Scientists are expected to spend up to 50 percent of their time on research, although, in practice, because of the heavy functional loads this fraction is usually much less than 50 percent. Support scientists are expected to spend only 20 percent of their time on research. All of these research funds are accounted in the NASA operating contract to AURA for STScI. However, this internal research support is covered in the NASA MO budget, not the R&A budget. The STScI is operated by the Association of Universities for Research in Astronomy, an independent not-for-profit research management corporation, under contract with NASA.

E.2 NASA TECHNOLOGY FUNDING

The committee notes that a significant amount of support for facilities and instrumentation development has been funded under NASA technology programs, primarily at the NASA centers. Data on the fraction of NASA technology funding applied to astronomy missions and instrumentation are not generally available; therefore, the committee is not able to estimate the magnitude of this component of funding for astronomy.

E.3 RESEARCH FUNDING AT NSF FACILITIES

In addition to their roles in providing service and access to the community, NSF centers also host scientific staff who pursue their own independent research some fraction of the time. This research is supported either by internal funds or through grants from other agencies (e.g., NASA). Unlike NASA centers, this support is generally covered in the main body of this report either under the center's operation budget, listed under operations support in the NSF summary or, if the grant support is from NASA, under the NASA R&A budget summary.

E.3.1 National Radio Astronomy Observatory

The NRAO is a federally funded research and development center of NSF. NRAO operates a number of facilities: the Very Large Array and Very Long Baseline Array in Socorro, New Mexico; the 140 Foot Telescope in Green Bank, West Virginia, soon to be closed in anticipation of the completion of construction and the beginning of operations of the Green Bank Telescope in early 2000; and the 12 Meter Telescope on Kitt Peak near Tucson, Arizona, to be closed when the Millimeter Array (MMA) begins interim operations. NRAO is conducting design and development work for the MMA, which is expected to join a similar European project, merging into a single international project to be called the Atacama Large Millimeter Array. NRAO also conducts a program of technology development in electronics for radio astronomy applications. Electronics developed by NRAO have been made available to the research community, including NASA missions (MAP), when there is no alternative commercial source. NRAO is the leading member of an international consortium to develop and support a data analysis system, AIPS++, applicable to the reduction of data from any radio telescope, worldwide. NRAO receives funds from NASA to participate in a JPL program of space very long baseline interferometry (VLBI), which combines the VLBA with an orbiting Japanese radio telescope to achieve higher angular resolution than is provided by Earth-based interferometer elements alone.

Observing time on NRAO telescopes is granted on the basis of scientific merit. Proposals are reviewed by outside referees. NRAO staff compete on the same basis and through the same procedures as do visiting observers. NRAO provides partial travel support and publication support to visiting observers.

The FY 1998 operating budget for the NRAO provided by NSF was about $31.7 million. This breaks down into the following categories: Socorro operations, 44 percent; Green Bank operations, 19 percent; Tucson operations, 6 percent; electronics development, 5 percent; research support, including software, for visitors and staff, 18 percent; administrative, 10 percent; equipment, 1 percent; less income (from sale of electronics and common cost recovery on outside contracts), 3 percent. The 1999 total of work for other agencies is about $3 million (NASA space VLBI and U.S. Naval Observatory for Earth rotation measures). The 1999 budget for MMA design and development is $9 million (1999 was the second year of a three-year MMA D&D program totaling $25 million that is being funded by NSF).

The NRAO is operated by Associated Universities, Inc., an independent not-for-profit research management corporation, under cooperative agreement with the NSF.

E.3.2 National Optical Astronomy Observatories

The NOAO is an FFRDC of the National Science Foundation. It comprises four divisions: Kitt Peak National Observatory (KPNO), Cerro Tololo Interamerican Observatory (CTIO), National Solar Observatory, and the United States Gemini Program/Science Operations (USGP/SCOPE). In addition, a number of groups provide central technical and administrative support to all the divisions. NOAO operates a number of telescopes on Kitt Peak, both nighttime and solar, including the 4-meter Mayall telescope, the 3.5-meter WIYN telescope (jointly owned with the University of Wisconsin, Indiana University, and Yale University), and the McMath-Pierce solar telescope. NOAO-operated telescopes on Cerro Tololo include the 4-meter Blanco telescope and the 1.5-meter telescope, and those on Sacramento Peak in New Mexico include the Vacuum Tower Telescope, the Evans Solar Facility, and the Hilltop Dome Facility.

Telescope time allocation at NOAO is proposal driven. Separate panels read proposals in galactic astronomy, extragalactic astronomy, and solar system studies and evaluate them on the basis of scientific merit. The NSF funds for operating the NOAO also provide support for 45 scientific staff, including postdocs. These staff are expected to spend half of their time on service-related activities and half on their own scientific research. The primary research areas are as follows:

- Optical nighttime astronomy,
- Infrared nighttime astronomy,
- Solar physics,
- Planetary research, and
- Theory.

The annual NSF budget for NOAO is approximately $27million, of which about 22 percent provides scientific staff salaries and benefits, 16 percent is used to develop and build instruments for the NOAO facilities, and 62 percent supports operations and maintenance of the facilities. The NOAO budget is divided among the divisions as follows: 27 percent for CTIO, 21 percent for KPNO, 16 percent for NSO (which also receives U.S. Air Force funding), and 9 percent for USGP/SCOPE. The remaining 27 percent is divided among the joint instrumentation program (11 percent) and central offices (16 percent). The central offices category includes outreach activities as well as administrative functions. NOAO operations funding from the NSF has been roughly constant in current dollars over the last decade.

The NOAO is managed by AURA, a nonprofit consortium of 29 U.S. institutions and six international affiliates under a cooperative agreement with the NSF.

E.3.3 International Gemini Project

The Gemini 8-Meter Telescopes Project is an international partnership to build and operate two 8-meter telescopes, one on Mauna Kea, Hawaii, and one on Cerro Pachon, Chile. The partners are the United States (47.6 percent), the United Kingdom (23.8 percent), Canada (14.3 percent), Australia (4.8 percent), Chile (4.8 percent), Argentina (2.4 percent), and Brazil (2.4 percent). The U.S. share is funded by NSF. The U.S. contribution was $92 million in the construction phase and will be approximately $7 million per year in the operations phase. Gemini-North is scheduled to go into operation in June 2000 and Gemini-South in June 2001. U.S. astronomers will have access to the Gemini telescopes through peer-reviewed proposals submitted to NOAO. At Gemini-North 51.6 percent of the time will be available to U.S. astronomers (with 10 percent for the University of Hawaii included in this number), and at Gemini-South, 41.6 percent of the time will be available to U.S. astronomers. The Gemini staff will include about 20 astronomers based at one of the two sites, who will be expected to spend 25 to 40 percent of their time on their own research.

Gemini is managed by AURA.

E.3.4 National Astronomy and Ionosphere Center

The NAIC is supported primarily through NSF's Division of Astronomical Sciences, but NSF's Division of Atmospheric Sciences supports atmospheric science research and NASA supports the solar system radar program. NAIC's main facility is the 305-meter Arecibo dish, which is the world's largest filled aperture radio telescope. It also operates several small optical telescopes for LIDAR (light detection and ranging) and passive atmospheric studies. The 305-meter telescope is used primarily for single-dish radio astronomy but is a powerful addition to the VLBI network because of its substantial contribution to the total system collecting area. Its radar astronomy capability is unequaled as a result of this system's recent enhancement. The Arecibo telescope had only limited availability for research during a major upgrade to install the Gregorian feed system and a ground screen. Nearly normal scientific operations resumed during the past year. Before the upgrade, approximately 80 percent of the time available for research on the large dish was used for radio astronomy, 5 percent of the time for radar astronomy, and 15 percent of the time for ionospheric studies. NAIC is operated by Cornell University under a cooperative agreement with the NSF.

E.4 DEPARTMENT OF ENERGY

Over the past two decades the boundaries between astrophysics and cosmology and nuclear and particle physics have become blurred. During this time, the Department of Energy has become an important player in the funding of astrophysics, both university and laboratory groups and large projects. DOE funding for astrophysics comes from the Divisions of High-Energy Physics (HEP) and Nuclear Physics. The DOE interest in astrophysics has been intellectual and bidirectional: nuclear physics and particle physics have important implications for astrophysics or cosmology; astrophysics and cosmology can be used to probe fundamental physics in regimes beyond the reach of terrestrial laboratories. Total DOE spending on astrophysics, both at the laboratories and in the university program and through HEP and Nuclear Physics, was estimated to be $30 million in FY 1997.

Most of the support for astrophysics comes from HEP. It supports university and laboratory groups through continuing grants and contracts (human level of effort) and additional money for major projects (equipment and the like). Here is a snapshot of FY 1997: overall, 230 groups were supported at 100 universities. The university program consisted of about 1,000 Ph.D.s (630 experimentalists and 370 theorists) and 520 graduate students (375 experimentalists and 145 theorists). The program included 30 tasks within the 230 groups that could be easily identified as astrophysics (a given university group may have multiple tasks within it). The head count in astrophysics was 75 Ph.D.s and 35 graduate students (about 7 percent of the university program). The total budget for this effort was about $13 million. Of this $13 million, about $2.3 million was designated for equipment for the shuttle/space station-based antimatter search (AMS), SuperKamiokande (solar, atmospheric, and supernova neutrino and proton decay detector), and MILAGRO and Granite (high-energy gamma-ray detectors). It is estimated that another $12 million was spent at DOE laboratories on astrophysics (Fermilab, Lawrence Berkeley National Laboratory [LBNL], Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Stanford Linear Accelerator Center [SLAC] all have significant efforts in astrophysics).

The major projects funded by DOE HEP in FY 1997 included three direct dark-matter searches (the cosmic axion search based at Livermore; the neutralino search currently at Stanford and moving to the Soudan Mine, known as CDMS I and II; and a monopole search at the Gran Sasso Laboratory in Italy, known as MACRO); the AMS on the Space Station; the Supernova Cosmology Project at LBNL (determination of deceleration of the universe using type Ia supernovae); the Sloan Digital Sky Survey at Fermilab (five-color digital sky survey and million-galaxy map of the universe); five high-energy cosmic-ray/gamma-ray experiments (MACRO, CASA-MIA array in Utah, Granite, MILAGRO, and AMANDA neutrino detector at the South Pole); and some support for cosmic microwave background experiments (Professor George Smoot's group at LBNL).

The Division of Nuclear Physics supports several theoretical nuclear astrophysics groups as well as the Institute for Nuclear Theory at the University of Washington, which has had a number of programs related to nuclear astrophysics and cosmology. DOE Nuclear Physics funds three solar-neutrino experiments: the Soviet American Gallium Experiment (SAGE), the European Gallium Solar-neutrino Detector (GALLEX), and the Sudbury Neutrino Observatory, which is just coming on line. It is estimated that the total spending for astrophysics-related work in FY 1998 was $5 million.

Astrophysics and cosmology are often cited as scientific drivers for the major accelerator facilities: the B-factory at SLAC (charge-parity conjugation [CP] violation and the origin of the matter-antimatter asymmetry in the universe); TeVatron at Fermilab (search for supersymmetry and the neutralino); and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven (the transition from quarkgluon plasma to hadrons in the early universe). DOE laboratory-funded astrophysics groups exist at Fermilab (both theory and experiment), LBNL (the Institute for Nuclear and Particle Astrophysics), Livermore (Institute of Geophysics and Planetary Physics), and Los Alamos (the T-8 theoretical astrophysics group).

DOE interest in astrophysics seems to be increasing and broadening. It is estimated that funding for astrophysics since FY 1997 has increased at about 10 percent per year and that 10 percent of DOE-supported high-energy physicists are involved in astrophysics research. Both DOE Nuclear Physics and DOE HEP are currently considering new projects: the Auger Observatory and HiResII (ultrahigh-energy cosmic rays), a kilometer-scale high-energy neutrino observatory (Km3), Veritas (teraelectron-volt gamma rays), GLAST (gamma-ray large-area space telescope), Icarus (solar and supernova neutrinos and dark matter), and Radioactive Ion Beam (Isotope Separator On Line [ISOL]), a new major facility to probe nuclei far from the line of stability (much of the scientific justification is astrophysics). Further, DOE now sees a second reason for its involvement in astrophysics: technology transfer. GLAST is a prime example of this (DOE detector expertise).

Currently, DOE HEP seeks advice on new initiatives in astrophysics through the Scientific Assessment Group for Experiments in Non-Accelerator Physics (SAGENAP). SAGENAP is co-chaired by P.K. Williams (DOE HEP) and Patricia Rankin (NSF Physics); it reports to NSF's Physics Division and DOE HEP. There has been some DOE interest in having the 1991 decadal survey committee evaluate future projects (Km^3 and ISOL).

The estimated total DOE spending on astrophysics and astrophysics-related programs, including university programs and laboratory activity, for FY 1997 was $25 million. Astrophysics funding increased by about 10 percent in FY 1998; the estimated increase for FY 1999 is also 10 percent.

E.5 DEPARTMENT OF DEFENSE

Department of Defense (DOD) funding of astronomy and astrophysics is difficult to determine because it is generally buried in a number of different DOD programs. The committee identified several programs with significant federal funding:

- U.S. Naval Observatory (USNO),
- Naval Research Laboratory (NRL),
- Air Force Phillips Laboratory,
- Lawrence Livermore National Laboratory,
- Lawrence Berkeley National Laboratory,
- The Aerospace Corporation,

- Sacramento Peak Observatory/National Solar Observatory, and
- National Reconnaissance Office (NRO).

A large portion of this astronomy funding is at USNO with a FY 1997 budget of approximately $10 million. This includes the operations in both Washington, D.C., and Flagstaff, Arizona, and a grants program. These programs primarily support positional astronomy. NRL carried out basic astrophysical programs with a FY 1997 budget of approximately $2 million. Funding for both of these programs has been relatively constant over the last ten years. The Air Force Phillips Laboratory supports at least three known components of astronomy and astrophysics. The Phillips Laboratory in Bedford, Massachusetts, supports infrared astronomy through its rocket and satellite programs. The Phillips Laboratory, New Mexico, has two major astronomical components, an adaptive optics program plus a 3.5-meter telescope that provides technology development for astronomy and a 3.7-meter telescope on Maui (Hawaii), which will be used by the University of Hawaii 10 percent of the time for astronomical research. The estimated level of funding for the University of Hawaii was about $1 million in FY 1997. Most of this funding was for instrumentation. The total development cost of the telescope is about $50 million.

DOD funding of solar research at NOAO/NSO was about $0.65 million in FY 1997. Finally, the Aerospace Corporation has a modest infrared astronomy program with a FY 1997 budget of $350,000.

E.6 SMITHSONIAN INSTITUTION

The Smithsonian Institution is a unique Trust Instrumentality of the federal government, which also supports a significant astronomical research endeavor, primarily through the Smithsonian Astrophysical Observatory. The federally funded activities of SAO center around research in seven areas: atomic and molecular physics, high-energy astrophysics, optical and infrared astronomy, planetary sciences, radio and geoastronomy, solar and stellar physics, and theoretical astrophysics. Within these activities, the two major facilities are the F.L. Whipple Observatory, which includes the Multiple Mirror Telescope (MMT; jointly operated with the University of Arizona) and which has been in operation since the 1960s, and the Submillimeter Array on Mauna Kea, currently under development. The conversion of the MMT to a single 6.5-meter telescope and 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 breakdown of federal research and operations support at SAO for the above fields is approximately as follows: atomic and molecular physics, 6 percent (which includes laboratory astrophysics, theoretical chemistry, and atmospheric chemistry); high-energy astrophysics, 8 percent (primarily experimental x-ray astronomy); optical and infrared astronomy, 32 percent (of which 40 percent is operations support for SAO's ground-based observatories, 45 percent is ground-based optical, and 15 percent is ground and space IR and gamma-ray astronomy); planetary sciences, 3 percent; radio astronomy, 17 percent; solar and stellar physics, 9 percent (about half each for solar and stellar); and theoretical astrophysics, 3 percent. The remaining fraction of federal support goes toward support activities (libraries, publications, etc.) and administration.

The budget for SAO in FY 1997 was approximately $16.8 million plus $7.24 million for major facility construction. This represents an increase of approximately 20 percent in the basic research and operations budget over 7 years (less than 3 percent per year) and a 34 percent increase over the same period for facility construction and instrumentation. The largest growth in the above scientific research areas has been in radio astronomy (because of the construction of the Submillimeter Array), and in theoretical astrophysics, which is only a small fraction of SAO's total scientific program. There have been small fractional increases in research support for high-energy and optical and infrared astronomy, which have been offset by declining support for administration, solar and stellar physics, and planetary sciences. Note that a small fraction (about 2 percent) of the SAO research support is derived from the Smithsonian's endowment and private funds.

E.7 NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

The National Institute of Standards and Technology (NIST) and the University of Colorado at Boulder jointly support JILA, formerly known as the Joint Institute for Laboratory Astrophysics. The senior scientific staff (or fellows) of JILA hold either faculty appointments at the university or civil service appointments at NIST. A decade ago there were several NIST positions in astrophysics, but these are no longer supported because of a change in the mission of NIST. Astrophysics continues to be supported from the university side, and NIST continues to maintain a gravitational physics program.

F

National Science Foundation Proposal Success Rates

The raw data on NSF proposal success rates for research proposals, for all of the Division of Astronomical Sciences (AST) and by field including ATI, are given in Table F.1. For the figures, proposal success fraction represents the number accepted versus the number received, but the average proposal size has been normalized to 1997 dollars using the deflators given in Appendix C. Data were assembled by R. Konkel, an NRC contractor, who served as a consultant to the committee and obtained data from M. Aizenman, deputy director of the NSF AST, and Guenther Riegler, director of the Research Program Management Division at NASA's Office of Space Science.

TABLE F.1 NSF Proposal Acceptance Rates and Average Funding, FY 1988 to FY 1999

	AST			ATI			EXC			GAL			SAA			PLA		
Year	Prop.	Succ.	Size	Prop.	Succ.	Size	Prop.	Succ.	Size	Prop.	Succ.	Size	Prop.	Succ.	Size	Prop.	Succ.	Size
1988	337	123	43,016	50	10	58,042	108	44	40,000	65	25	43,000	88	32	34,700	20	7	50,000
1989	312	139	49,980	33	17	62,400	85	32	50,874	49	20	53,475	106	55	45,512	27	9	56,133
1990	286	150	53,000	31	25	59,248	78	43	49,700	61	30	59,714	80	36	57,333	18	10	41,083
1991	291	148	53,919	39	26	68,000	88	48	58,792	58	26	68,333	89	37	41,550	12	7	35,000
1992	321	151	57,292	44	24	77,291	78	38	68,000	49	21	56,100	126	53	47,300	13	8	54,900
1993	357	114	60,069	54	21	83,000	87	29	60,267	57	23	63,963	134	53	48,483	19	2	8,133
1994	354	166	51,850	50	30	71,436	76	32	56,741	48	19	45,948	108	50	41,950	41	21	40,000
1995	382	118	55,417	50	11	97,913	72	21	66,702	52	20	53,147	126	31	62,000	32	10	40,000
1996	391	107	67,753	26	7	168,735	95	24	55,000	73	15	81,667	95	28	58,833	36	8	60,907
1997	489	158	64,000	48	18	102,544	119	43	65,000	82	22	62,500	112	31	60,000	43	15	46,991
1998	366	102	81,957	45	14	140,541	133	32	99,989	58	14	72,572	103	31	57,555	41	11	64,898
1999	419	109	77,795	38	8	149,579	124	32	85,844	48	11	83,882	114	30	66,313	31	4	68,158

NOTES: Acronyms are defined in Appendix H. Prop. = number of proposals received; Succ. = number of proposals accepted; Size = average grant size in current-year dollars. Funding for FY 1999 not yet available.

G

Notes on Figures, Tables, and Other References

OVERALL FUNDING

In Figure 2.2 in Chapter 2, overall funding data for 1981 to 1985 are taken from the 1991 Decadal Report, adjusted via the standard inflation factors to FY 1997. Data for 1986 to 1999 are taken from R. Konkel's (NRC contractor) spreadsheets. For the period from 1986 to 1989, the agreement between the 1991 Decadal Report and Konkel is in the 2 to 4 percent range.

In Figure 2.3, NSF funding, data for 1981 to 1985 are again taken from the 1991 Decadal Report; data for 1986 to 1999 are taken from R. Konkel's spreadsheets. For the period from 1986 to 1989, the agreement between the two sets of numbers is good, better than 1 percent.

In Figure 2.4, NSF grant funding data for 1981 to 1987 are taken from the 1991 Decadal Report. For the years 1988 to 1997, data are from Konkel: the number of grants is estimated as the number of new awards multiplied by the mean new award duration averaged over the three previous years. The rationale for this approach is that the grants are of roughly three-year duration and have to be smoothed.

In Figure 2.5 , the NASA astronomy budget data for 1981 to 1985 are from the 1991 Decadal Report; data for 1986 to 1999 are from Konkel. Much of the earlier material appeared in the 1998 Space Studies Board report *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis.*

STUDENTS AND DEGREES

Astronomy doctorate production and graduate enrollment figures are taken from the AIP *Enrollments and Degrees Report* (Patrick J. Mulvey and Starr Nicholson, *Enrollments and Degrees Report,* AIP Publication No. R-151.35, American Institute of Physics, College Park, Maryland, 2000) and from the AAS report on Graduate Education (Stephen Strom et al., “The American Astronomical Society's Examination of Graduate Education in Astronomy,” *Bulletin of the American Astronomical Society,* volume 29 (1997), page 1426). Figures for 1988 to 1998 are from the *Enrollments and Degrees Report.* Note that one of the problems inherent in an effort like this is that when there is an overlap in coverage, both sources agree qualitatively but not quantitatively—there is some interpretation of what constitutes a doctorate in astronomy or astrophysics, especially when the doctorate is granted by a joint physics and astronomy department. Enrollment numbers for 1985 to 1987 are scaled from the AAS report to the AIP mean by the AIP/AAS ratio for the years with overlap. The actual figures and estimates are shown in Table G.1.

TABLE G.1 NRC/AIP Data on Astronomy Ph.D. Production in the United States, 1973 to 1998

	Ph.D.s Granted							Enrolled Graduate Students	
Year	S+E Total	Engineering	Physical Science	Astronomy	Physics	Life Science	Math	Astronomy	Physics
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1973	—	—	—	131	—	—	—	—	—
1974	—	—	—	133	—	—	—	—	—
1975	—	—	—	131	—	—	—	—	—
1976	—	—	—	150	—	—	—	—	—
1977	—	—	—	120	—	—	—	—	—
1978	—	—	—	138	—	—	—	—	—
1979	—	—	—	115	—	—	—	—	—
1980	—	—	—	121	—	—	—	—	—
1981	18,914	2,528	2,627	109	906	5,442	960	—	—
1982	18,961	2,646	2,694	102	912	5,530	940	—	—
1983	19,274	2,781	2,814	115	928	5,395	987	—	—
1984	19,470	2,913	2,851	98	982	5,599	993	—	—
1985	19,664	3,166	2,934	100	980	5,632	998	660	—
1986	20,207	3,376	3,120	109	1,078	5,574	1,128	680	—
1987	20,694	3,712	3,238	100	1,137	5,615	1,190	700	—
1988	21,814	4,187	3,350	130	1,172	6,008	1,264	731	13,143
1989	22,706	4,543	3,261	113	1,161	6,176	1,471	780	13,361
1990	23,824	4,894	3,524	128	1,265	6,458	1,597	842	13,708
1991	25,064	5,214	3,626	125	1,286	6,764	1,839	914	14,065
1992	25,787	5,438	3,781	134	1,403	6,974	1,927	935	14,534
1993	26,640	5,698	3,699	145	1,399	7,257	2,026	939	14,430
1994	27,501	5,822	3,977	144	1,548	7,577	2,021	901	14,201
1995	27,865	6,008	3,841	173	1,479	7,742	2,187	905	13,285
1996	28,554	6,305	3,838	192	1,485	8,084	2,043	874	12,596
1997	28,241	6,052	3,711	197	1,379	8,077	2,001	837	11,786
1998	—	—	—	—	—	—	—	757	11,302

NOTE: Columns 2 to 8, Ph.D.s granted, from NRC Office of Scientific and Engineering Personnel and from AAS graduate education study (*The American Astronomical Society's Examination of Graduate Education in Astronomy,* available online at <http://www.aas.org/publications/baas/v29n5/edrpt.html>). Numbers for astronomy include astronomy and astrophysics dissertations produced in physics departments. Columns 9 and 10, enrolled graduate students from AAS graduate education study or from AIP enrollments and degrees report (AIP Publication R151.35).

For the data used in Figure 4.3 Figure 4.5 to Figure 4.6, Chapter 4, the number of papers published per year showed a considerable increase over the period studied, with two anomalies caused by changes in the number of issues per month: *The Astrophysical Journal* changed between 1989 and 1992, while *Monthly Notices* changed between 1995 and 1997. To remove this effect, the committee presents all results as fractions of the total for that year.

For Table 5.7, Chapter 5, figures for the NASA R&A budget are from Guenther Riegler at NASA headquarters and were compiled by Board on Physics and Astronomy program officer Joel Parriott.

Overall DOE astrophysics funding data are from Jim Stone in the program office at DOE HEP. They do not include nuclear physics spending on programs that are astrophysics related.

H

Acronyms

A&A	Astronomy and Astrophysics
AAAS	American Association for the Advancement of Science
AAS	American Astronomical Society
AASC	Astronomy and Astrophysics Survey Committee (Decadal Reports)
AASTRA	AAS membership program for K-12 science teachers
ADP	Astrophysics Data Program (NASA)
ADS	Astrophysical Data System (NASA)
AGN	active galactic nuclei
AIP	American Institute of Physics
AIPS	Radio Astronomy Data Analysis System (also AIPS++)
AJ	*Astronomical Journal*
ALMA	Atacama Large Millimeter Array (previously, the MMA)
AMANDA	Antarctic Muon and Neutrino Detector Array
AMS	Space Station Antimatter Search program
AO	Announcement of Opportunity
ApJ	*Astrophysical Journal*
APS	American Physical Society
ARC	Astronomical Research Corporation
ASCA	Advanced Satellite for Cosmology and Astrophysics (Japan)
AST	Division of Astronomical Sciences (NSF)
ATI	Advanced Technology and Instrumentation program (NSF)
ATM	Division of Atmospheric Sciences (NSF)
ATP	Astrophysical Theory Program
AUI	Associated Universities Incorporated
AURA	Association of Universities for Research in Astronomy
AXAF	Advanced X-ray Astronomy Facility, now known as Chandra
BAAS	*Bulletin of the American Astronomical Society*
BATSE	Burst and Transient Source Experiment, on CGRO
BIMA	Berkeley-Illinois-Maryland Array
BPA	Board on Physics and Astronomy (NRC)
CAA	Committee on Astronomy and Astrophysics (NRC)
CARA	California Association for Research in Astronomy
CAREER	NSF Program for Young Investigators
CASA-MIA	University of Chicago Air Shower Array and University of Michigan Muon Detector (in Utah)
CDMS I and II	Cryogenic Dark Matter Search: I, Stanford University; II, Tower Soudan Mine

CDP	Cross Directorate Programs
CGRO	Compton Gamma Ray Observatory
COBE	Cosmic Background Explorer
CoI	coinvestigator
COMPTEL	Imaging Compton Telescope
CP	charge-parity conjugation
CR	cosmic ray
CSO	Caltech Submillimeter Observatory
CTIO	Cerro Tololo Interamerican Observatory
CY	calendar year
DA	data analysis
DDRF	Director's Discretionary Research Fund
DOD	Department of Defense
DOE	Department of Energy
EGRET	Energetic Gamma Ray Experiment Telescope on CGRO
EPSCoR	Experimental Program to Stimulate Competitive Research (NSF)
ESA	European Space Agency
ESO	European Southern Observatory
ESP	Education and Special Programs
EUVE	Extreme Ultraviolet Explorer
EXC	Extragalactic and Cosmology program (NSF)
EXGAL	Extragalactic Astronomy and Cosmology program (NSF)
FCRAO	Five College Radio Astronomy Observatory
FFRDC	Federally Funded Research and Development Center
FIR	far infrared
FTE	full-time equivalent
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	fiscal year
GAL	Galactic Astronomy program (NSF)
GALLEX	European Gallium Solar-neutrino Detector
GBT	Green Bank Telescope
GDP	gross domestic product
GINGA	Third Japanese X-ray Astronomy Satellite
GISS	Goddard Institute for Space Studies
GLAST	Gamma Ray Large Area Space Telescope
GO	Guest Observer program
GP-B	Gravity Probe B
GPRA	Government Performance and Results Act of 1993
GSFC	Goddard Space Flight Center
GTO	Guaranteed Time Observer (usually instrument or telescope builder)
HALCA	Highly Advanced Laboratory for Communications and Astronomy
HEA	High-Energy Astrophysics (DOE)
HEAO	High Energy Astrophysics Observatory (HEAO-B = Einstein)
HEP	High Energy Physics Division (DOE)
HET	Hobby-Eberly Telescope

HiResII	Ultrahigh-Energy Cosmic Ray Detector
HSC	House Science Committee
HST	Hubble Space Telescope
IPA	Intergovernmental Personnel Act
IR	infrared
IRTF	Infrared Telescope Facility
ISM	interstellar medium
ISO	European Infrared Space Observatory
ISOL	Isotope Separator On Line
IUE	International Ultraviolet Explorer
JPL	Jet Propulsion Laboratory
KAO	Kuiper Airborne Observatory
KDI	Knowledge and Distributed Intelligence
KPNO	Kitt Peak National Observatory
LBNL	Lawrence Berkeley National Laboratory
LBT	Large Binocular Telescope
LEXEN	Life in Extreme Environments
LIDAR	light detection and ranging
LIGO	Laser Interferometer Gravitational-wave Observatory
LISA	Laser Interferometer Space Antenna
LTSA	Long Term Space Astrophysics
MACRO	Monopole Particle Search at Gran Sasso Laboratory
MAP	Microwave Anisotropy Probe
MDM	University of Michigan, Dartmouth College, and Massachusetts Institute of Technology; now University of Michigan, Dartmouth College, Ohio State University, and Columbia University
MILAGRO	High Energy Gamma Ray Detector
MMA	Millimeter Array, now ALMA
MMT	Multiple Mirror Telescope
MO	mission operations
MO&DA	Mission Operations and Data Analysis
MPS	Mathematics and Physical Sciences Directorate (NSF)
MRE	major research equipment
MRI	Major Research Instrumentation program (NSF)
MSFC	Marshall Space Flight Center
NAIC	National Astronomy and Ionospheric Center
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NGST	Next Generation Space Telescope (NASA)
NICMOS	Near Infrared Camera and Multi Object Spectrograph (HST)
NIR	near infrared
NIST	National Institute of Standards and Technology
NOAO	National Optical Astronomy Observatories
NRA	NASA Research Announcement
NRAO	National Radio Astronomy Observatory
NRC	National Research Council

NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NSB	National Science Board
NSF	National Science Foundation
NSO	National Solar Observatory
OC	other construction
OI	observational infrared
OIR	optical and infrared
OMA	Office of Multidisciplinary Affairs (NSF)
OMB	Office of Management and Budget
OO	observational optical
OPP	Office of Polar Programs (NSF)
OPS	operations
OR	observational radio
OSS	Office of Space Science (NASA)
OVRO	Owens Valley Radio Observatory (Caltech)
PECASE	Presidential Early Career Awards for Scientists and Engineers (NSF)
PHY	Physics Division (NSF)
PI	principal investigator
PL	planetary
PLA	Planetary Astronomy program (NSF)
POWRE	Professional Opportunities for Women in Research and Education (NSF)
PYI	Presidential Young Investigator (now CAREER)
R&A	research and analysis
R&D	research and development
REU	Research Experience for Undergraduates
RHIC	Relativistic Heavy Ion Collider (Brookhaven)
ROSAT	Röentgen Satellite (Germany)
R&RA	research and related activities
RSM	Radio Spectrum Management
RTOP	Research and Technology Objectives and Plans Program
RXTE	Rossi X-ray Timing Experiment
SAA	Stellar Astronomy and Astrophysics program (NSF)
SAGE	Soviet-American Gallium Experiment (for neutrinos)
SAGENAP	Scientific Advisory Group for Non-accelerator Physics (DOE)
SALT	South African Large Telescope
SAO	Smithsonian Astrophysical Observatory
SDSS	Sloan Digital Sky Survey
SETI	Search for Extraterrestrial Intelligence
SIRTF	Space Infrared Telescope Facility
SLAC	Stanford Linear Accelerator Center
SMA	Submillimeter Array
SMM	Submillimeter/Millimeter
SNO	Sudbury Neutrino Observatory
SO	Solar

SOAR	Southern Observatory for Astronomical Research (4-meter telescope at CTIO)
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOHO	Solar Heliospheric Observatory (ESA-NASA)
SRS	Division of Science Resources Studies (NSF)
SSB	Space Studies Board (NRC)
ST	Stellar
STC	Science and Technology Center
STIS	Space Telescope Imaging Spectrometer
STScI	Space Telescope Science Institute
Subaru	Japanese 8-meter Telescope (Hawaii)
TH	Theory
UHE	ultrahigh energy
USGP/SCOPE	U.S. Gemini Program/Science Operations Division (NOAO)
USNO	United States Naval Observatory
UV	ultraviolet
VERITAS	Ultrahigh-Energy Gamma Ray Array
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLT	European Very Large Telescope (4 × 8-meters)
WIYN	Wisconsin, Indiana, Yale, and NOAO 3.5-meter Telescope (KPNO)
YALO	Yale, AURA, University of Lisbon, and Ohio State 1-meter Telescope Consortium