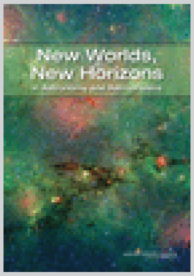

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New Worlds, New Horizons

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Board on Physics and Astronomy

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Cover: Complexity abounds in the universe, especially during the birth phases of stars and planetary systems. The M17 region, also known as the Omega Nebula, in the constellation Sagittarius is rich in massive stars, including those recently formed and already impacting their environment (bright nebulous regions—e.g., back lower), as well as those still in the process of formation within cold dense clouds (dark regions—e.g., front center). Provinces such as this within our galaxy and others allow astronomers to understand and quantify the cycling of matter and energy within the cosmic ecosystem. The image depicts mid-infrared emission at 3.6- to 24-micrometer wavelengths as detected by NASA's Spitzer Space Telescope, although the region has been studied from high-frequency gamma-ray to low-frequency radio energies. Image courtesy of NASA/JPL-Caltech.

Dedication (p. xxxiii): Photo courtesy of American Astronomical Society.

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Preface

The summary of the charge to the Committee for a Decadal Survey of Astronomy and Astrophysics reads:

> This decadal survey of astronomy and astrophysics is charged to survey the field of space- and ground-based astronomy and astrophysics and to recommend priorities for the most important scientific and technical activities of the decade 2010-2020. The principal goals of the study are to carry out an assessment of activities in astronomy and astrophysics, including both new and previously identified concepts, and to prepare a concise report that will be addressed to the agencies supporting the field, the congressional committees with jurisdiction over those agencies, the scientific community, and the public.

The complete statement of task is given in Appendix E.

Essentially, the committee was asked to consider (1) the acquisition, analysis, and interpretation of observations of the cosmos, including technology development and new facilities needed, as well as the computational and theoretical framework for understanding the observations; (2) the extent of the common ground between fundamental physics and cosmology as well as other areas of interface with related scientific disciplines, as appropriate; and (3) the federal research programs that support work in the field of astronomy and astrophysics, including programs at the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and selected aspects of the physics programs at the NSF and the Department of Energy (DOE). Only physics topics with a strong overlap with astronomy and astrophysics were within the study charge. In addition, only ground- and not space-based solar astronomy was to be considered.[1] Direct detection of dark matter was also excluded from prioritization. The survey was also charged to assess the infrastructure of the field, broadly defined, and to consider the importance of balance within and among the activities sponsored by the various agencies that support research in astronomy and astrophysics.

The committee was asked to formulate a decadal research strategy with recommendations for initiatives in priority order within different categories (related to the size of the activities and their home agencies). In addition to reviewing individual initiatives, aspects of infrastructure, and so on, the committee also was asked to make a judgment about how well the current program addresses the range of scientific opportunities and how it might be optimized—all the time guided by the principle that the priorities would be motivated by maximizing future scientific progress.

An important characteristic of contemporary astronomy, and therefore of this survey, is that most research is highly collaborative, involving international, interagency, private, and state partnerships. This feature has expanded the scope of what is possible but also makes assessment and prioritization more complicated. Another important characteristic is that astronomy remains a discovery-oriented science and that any strategy designed to optimize the science must leave room for the unexpected.

In contrast to previous surveys of the field, the prioritization process for this one included consideration of those unrealized projects that had been recommended in previous decadal surveys but had not had a formal start, alongside new research activities[2] that have emerged more recently from the research community. The survey was asked to review the technical readiness of the projects being considered for prioritization, assess various sources of risk, and develop independent estimates of the cost and schedule risks of the activity with help from an independent contractor hired by the National Research Council (NRC), the Aerospace Corporation. There were also instructions to consider and make recommendations relating to the allocation of future budgets and to address choices that may be faced, given a range of budget scenarios—including establishing criteria on which the recommendations depend, and suggesting strategies for the agencies on how to rebalance programs within budgetary scenarios upon failure of one or more of the criteria.

[1] A newly initiated NRC decadal survey on heliophysics will consider space-based research activities.

[2] In this context, "activities" include any project, telescope, facility, mission, or research program of sufficient scope to be identified separately in the committee's report. The selection of subject matter was guided by the content of these programs.

STUDY PROCESS AND PARTICIPANTS

The committee began its work in the fall of 2008 with preparations for the first plenary meeting of the Astro2010 Survey Committee in December 2008. The first task was to define the work for the nine expert panels appointed in early 2009 by the NRC to assist the committee in the execution of its charge. The five Science Frontier Panels (SFPs) defined and articulated the themes for the science case that underpins the survey recommendations. The four Program Prioritization Panels (PPPs) conducted an in-depth study of the technical and programmatic issues related to the 100 or so research activities—in total more than 10 times the program that could be supported under any credible budget—that the community presented to the survey in the months that followed.

The nine appointed panels comprised 123 members drawn from across all of astronomy and astrophysics. In the first phase of the survey, the five SFPs worked to identify science themes that define the research frontiers for the 2010-2020 decade in five areas: Cosmology and Fundamental Physics, the Galactic Neighborhood, Galaxies Across Cosmic Time, Planetary Systems and Star Formation, and Stars and Stellar Evolution. Drawing on the 324 white papers on science opportunities submitted to the NRC in response to an open call from the committee to the astronomy and astrophysics research community,[3] as well as on briefings received from federal agencies that provide support for the field, the SFPs strove to identify the scientific drivers of the field and the most promising opportunities for progress in research in the next decade, taking into consideration those areas where the technical means and the theoretical foundations are in place to enable major steps forward. The SFPs were instructed to avoid advocacy for prioritization of specific new missions, telescopes, and other research activities. They also worked ahead of and therefore independent of the PPPs. The input of the SFPs to the committee was organized around four science questions ripe for answering and general areas with unusual discovery potential. The SFPs, and especially their chairs, dealt with the considerable challenge of anticipating future scientific developments and making tough choices with careful deliberation and collegiality.

In the second phase of the survey, the PPPs were charged to develop a ranked program of research activities in four programmatic areas: Electromagnetic Observations from Space; Optical and Infrared Astronomy from the Ground; Particle Astrophysics and Gravitation; and Radio, Millimeter, and Submillimeter Astronomy from the Ground. In addition to the draft science questions and discovery areas received from the SFP chairs at a joint meeting held in May 2009, the PPPs also reviewed the more than 100 proposals for research activities presented

[3] The set of white papers submitted is available at http://sites.nationalacademies.org/BPA/BPA_050603. Accessed May 2010.

by the astronomy and astrophysics community for consideration by the survey.[4] In addition the PPPs received briefings from federal agencies, project proponents, and other stakeholders at public sessions held in June 2009 at the summer meeting of the American Astronomical Society in Pasadena, California. In their final assembly of priorities, the PPPs also took into account assessments of cost and schedule risk, and of the technical readiness of the research activities under consideration for prioritization. Each PPP proposed a program of prioritized, balanced, and integrated research activities, reflecting the results of its in-depth study of the technical and programmatic issues and of its consideration of the results of the independent technical evaluation and cost and schedule risk estimate. The committee received draft reports of the PPPs' input on proposed programs at its fourth committee meeting in October 2009. All four PPPs and especially their chairs dealt with the daunting task of choosing, with objectivity and on the basis of their broad expertise, just a few of the many scientifically exciting and credible proposals in front of them. The reports of the five SFPs and the four PPPs are collected in a separate volume of this survey report.[5]

In addition to the nine panels, six Infrastructure Study Groups (ISGs) also provided input for the committee's consideration. Consisting of 71 volunteer consultants drawn for the most part from the astronomy and astrophysics community, the ISGs gathered and analyzed data on "infrastructural" issues in six areas—Computation, Simulation, and Data Handling (including archiving of astronomical data); Demographics (encompassing astronomers and astrophysicists working in different environments and subfields); Facilities, Funding, and Programs (including infrastructure issues such as support for laboratory astrophysics and technology development and theory); International and Private Partnerships; Education and Public Outreach; and Astronomy and Public Policy (focusing on benefits to the nation that accrue from federal investment in astronomy and the potential contributions that professional astronomers make to research of societal importance, and mechanisms by which the astronomy community provides advice to the federal government)—to describe recent trends and past quantifiable impacts on research programs in astronomy and astrophysics. The ISGs provided preliminary factual material to the committee and the PPPs at the May 2009 meeting, and their final internal working papers were made available to the committee in the fall of 2009. The members of the six ISGs are listed in the section that follows this preface.

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[4] For more information see http://sites.nationalacademies.org/BPA/BPA_049855. Accessed May 2010.

[5] National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2011.

The five SFPs, four PPPs, and six ISGs were crucial components of the survey, not only for the content and critical analysis they supplied but also because of the connections they provided to the astronomy and astrophysics community. Moreover the panels and study groups completed a Herculean set of tasks in an extraordinarily short time. The results of their efforts were essential to the deliberations of the committee, the success of whose work depended critically on the sequential and orderly flow of information from the SFPs to the PPPs and then to the committee as provided for in the survey plan and structure. The committee acknowledges with heartfelt thanks the volunteers from the astronomy and astrophysics community who served on the panels and study groups. Their reports stand testament to the hard work done by the members, and especially their chairs, work whose full value will be recognized through the decade to come.

In addition, the survey as a whole benefited immensely from the broader participation of the astronomy and astrophysics community, which, over the course of the study, and in particular in the first half of 2009, undertook a massive effort to provide input to the survey process. Included were informal reports from 17 community town hall meetings, in addition to more than 450 white papers on topics including science opportunities, the state of the profession and infrastructure, and opportunities in technology development, theory, computation, and laboratory astrophysics. Critical to the success of the nine panels' and six study groups' work, these inputs were also an early product of the survey in that the white papers and various reports were made available on NRC Web pages.[6] Far more important than the quantity, however, is the quality of the input. As public documents, many of these essays and proposals have already been widely cited in the professional literature. Although it will be many years before the significance of the survey can be assessed, the impact of the community input is already assured. On behalf of the committee and the panels, sincere thanks are extended to the volunteers from the research community who gave so much of their time to formulate this backbone of information and data as input for the Astro2010 survey process.

In addition to the 27 panel meetings conducted over the course of this survey, the survey committee itself met in person six times and held more than 100 teleconferences between December 2008 and May 2010. There were also detailed briefings from Jon Morse on behalf of NASA, Craig Foltz on behalf of NSF, and Dennis Kovar on behalf of DOE. All three agencies are thanked for their generous sponsorship of the survey and patient responses to requests for information that provided policy and budgetary context. In addition, the committee was pleased to receive critical perspectives from the U.S. Congress, the Office of Science and Tech-

[6] The set of white papers submitted is available at http://sites.nationalacademies.org/BPA/BPA_050603. Accessed May 2010. For more information see http://sites.nationalacademies.org/BPA/BPA_049855. Accessed May 2010.

nology Policy, and the Office of Management and Budget. Kevin Marvel and Kate Kirby, executive officers of the American Astronomical Society and the American Physical Society, respectively, offered their insights and arranged important interfaces to the community. Members of the committee met regularly with the Board on Physics and Astronomy and the Space Studies Board, whose members provided wise feedback and advice.

The committee undertook the hard and painful task, necessitated by the relatively severe financial constraints under which the agencies expect to have to operate, of consolidating the rich science opportunities and selecting from the many exciting and realizable activities presented to it. It established a set of criteria and, through a deliberative process, developed the program that is proposed in this report. The science objectives were first organized into three general themes enhanced by discovery areas. These themes were then focused into three science objectives for the decade, labeled "Cosmic Dawn," "New Worlds," and "Physics of the Universe." The activities recommended to optimize addressing these objectives were organized into large, medium, and small activities in space and on the ground. The committee also took into account the organization of research programs in astronomy within the current federal agency structure.

ADDITIONAL ACKNOWLEDGMENTS AND COMMENTS

The complexity of this process could have been overwhelming but for the support of the NRC staff at the Board on Physics and Astronomy and the Space Studies Board: Carmela Chamberlain, LaVita Coates-Fogle, Brian Dewhurst, Beth Dolan, Catherine Gruber, Caryn Knutsen, James Lancaster, David Lang, Robert L. Riemer, Richard Rowberg, Brant Sponberg, and Teri Thorowgood. These dedicated supporters of the field undertook the formidable task of making all these meetings work, receiving and organizing all the input, and providing the logistical and tactical support that allowed the committee to remain on task, on schedule, and on budget over the course of close to 2 years. In addition the committee benefited from the inputs provided by three younger members of the community who served as NRC Mirzayan Policy Fellows over the course of the survey—Baruch Feldman, Michael McElwaine, and Leslie Chamberlain. Christine Aguilar provided logistical support from Stanford.

On behalf of the committee, I express my personal gratitude to all of the above. I also thank Ralph Cicerone, president of the National Academy of Sciences, for his unfailing support and helpful guidance. Donald Shapero, director of the Board on Physics and Astronomy, likewise kept watch over the process and used his experience to keep it on track. Michael Moloney directed the survey from the start with remarkable efficiency, foresight, and tact and did not stint in his effort after he also took on the directorship of the Space Studies Board. Lastly, I acknowledge

every one of my 22 colleagues on the committee, who all worked extremely hard to learn about and then represent the whole field of astronomy and astrophysics. I am grateful for all that they have taught me and for their generous and good-natured support over the past 2 years. Among these must be singled out Martha Haynes, John Huchra, and Marcia Rieke, who acted so ably as vice chairs, and, especially, Lynne Hillenbrand, who served wisely, patiently, and tirelessly as executive officer. Each of these contributions was essential to the completion of the survey.

The committee has been faced with making difficult choices in what is widely agreed are sobering times. Our national finances are experiencing significant stress, and although at the time of this report's release the support of the current administration and Congress for science is remarkable, this survey has had to act responsibly in considering the scope of the program it can envision. This happens in the context of reporting at a singular time in the history of astronomy, one of remarkable ongoing discovery and unlimited possibility. All who have served on or worked with the committee have been conscious of their personal good fortune to be living at this time and the wonderful scientific opportunity that today's astronomers enjoy to seek new worlds and reach out to the new horizons of the universe. With the aid of the facilities operational today, those that are already started and will be completed during this decade, and those that are recommended to be started soon, this promises to be another extraordinary decade of discovery.

Roger D. Blandford, *Chair*
Committee for a Decadal Survey of
Astronomy and Astrophysics

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The Committee for a Decadal Survey of Astronomy and Astrophysics acknowledges with gratitude the contributions of the members of the six Astro2010 Infrastructure Study Groups, who gathered information on issues related to the broad topics listed below.

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Acknowledgment of Reviewers

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

Jonathan Bagger, Johns Hopkins University,
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Louis J. Lanzerotti, New Jersey Institute of Technology, and Bernard F. Burke, Massachusetts Institute of Technology. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Astronomy is in a golden age with spectacular discoveries such as the first extrasolar planets, pinning down the age of the Universe, dark energy, galactic black holes, and galaxies formed only a few hundred million years after the Big Bang as just some of the drivers for new questions. . . . Whatever else happens, we are privileged to be a part of this enterprise.

—John Huchra (*AAS Newsletter*, Issue 152, May/June 2010)

The Committee for a Decadal Survey of Astronomy and Astrophysics dedicates this report to a dear friend and valued colleague, John P. Huchra, who served as a vice chair for the decadal survey.

Executive Summary

Our view of the universe has changed dramatically. Hundreds of planets of startling diversity have been discovered orbiting distant suns. Black holes, once viewed as an exotic theoretical possibility, are now known to be present at the center of most galaxies, including our own. Precision measurements of the primordial radiation left by the big bang have enabled astronomers to determine the age, size, and shape of the universe. Other astronomical observations have also revealed that most of the matter in the universe is dark and invisible and that the expansion of the universe is accelerating in an unexpected and unexplained way. Recent discoveries, powerful new ways to observe the universe, and bold new ideas to understand it have created scientific opportunities without precedent.

This report of the Committee for a Decadal Survey of Astronomy and Astrophysics proposes a broad-based, integrated plan for space- and ground-based astronomy and astrophysics for the decade 2012-2021. It also lays the foundations for advances in the decade 2022-2031. It is the sixth in a sequence of National Research Council (NRC) decadal studies in this field and builds on the recommendations of its predecessors. However, unlike previous surveys, it reexamines unrealized priorities of preceding surveys and reconsiders them along with new proposed research activities to achieve a revitalized and timely scientific program. Another new feature of the current survey is a detailed analysis of the technical readiness and the cost risk of activities considered for prioritization. The committee has formulated a coherent program that fits within plausible funding profiles considering several different budget scenarios based on briefings by the sponsoring agencies—the National Aeronautics and Space Administration, the National Science Foundation, and the Department of Energy. As a result, recommended priorities reflect an executable balance of scientific promise against cost, risk, and readiness. The international context also played an important role in the committee's deliberations, and many of the large projects involve international collaboration as well as private donors and foundations.

The priority science objectives chosen by the survey committee for the decade 2012-2021 are searching for the first stars, galaxies, and black holes; seeking nearby habitable planets; and advancing understanding of the fundamental physics of the universe. These three objectives represent a much larger program of unprecedented opportunities now becoming within our capability to explore. The discoveries made will surely lead to new and sometimes surprising insights that will continue to expand our understanding and sense of possibility, revealing new worlds and presenting new horizons, the study of which will bring us closer to understanding the cosmos and our place within it.

This report recommends a program that will set the astronomy and astrophysics community firmly on the path to answering some of the most profound questions about the cosmos. In the plan, new optical and infrared survey telescopes on the ground and in space will employ a variety of novel techniques to investigate the nature of dark energy. These same telescopes will determine the architectures of thousands of planetary systems, observe the explosive demise of stars, and open a new window on the time-variable universe. Spectroscopic and high-spatial-resolution imaging capabilities on new large ground-based telescopes will enable researchers to discern the physical nature of objects discovered at both shorter and longer wavelengths by other facilities in the committee's recommended program. Innovative moderate-cost programs in space and on the ground will be enhanced so as to enable the community to respond rapidly and flexibly to new scientific discoveries. Construction will begin on a space-based observatory that employs the new window of gravitational radiation to observe the merging of distant black holes and other dense objects and to precisely test theories of gravity in new regimes that we can never hope to study on Earth. The foundations will be laid for studies of the hot universe with a future X-ray telescope that will search for the first massive black holes, and that will follow the cycling of gas within and beyond galaxies. Scientists will conduct new ground-based experiments to study the highest-energy photons emitted by cosmic sources. At the opposite end of the electromagnetic spectrum, radio techniques will become powerful enough to view the epoch when the very first objects began to light up the universe, marking the transition from a protracted dark age to one of self-luminous stars. The microwave background radiation will be scrutinized for the telltale evidence that inflation actually occurred. Perhaps most exciting of all, researchers will identify which nearby stars are orbited by planets on which life could also have developed.

Realizing these and an array of other scientific opportunities is contingent on maintaining and strengthening the foundations of the research enterprise that are essential in the cycle of discovery—including technology development, theory, computation and data management, and laboratory experiments, as well as, and in particular, human resources. At the same time, the greatest strides in understanding often come from bold new projects that open the universe to new discoveries, and such projects thus drive much of the strategy of the committee's proposed program. This program requires a balance of small, medium, and large initiatives on the ground and in space. The large and medium elements within each size category are as follows:

- ***In Space:*** (Large-scale, in priority order) *Wide-Field Infrared Survey Telescope* (WFIRST)—an observatory designed to settle essential questions in both exoplanet and dark energy research, and which will advance topics ranging from galaxy evolution to the study of objects within our own galaxy. *The Explorer Program*—augmenting a program that delivers a high level of scientific return on relatively moderate investment and that provides the capability to respond rapidly to new scientific and technical breakthroughs. *Laser Interferometer Space Antenna* (LISA)—a low-frequency gravitational wave observatory that will open an entirely new window on the cosmos by measuring ripples in space-time caused by many new sources, including nearby white dwarf stars, and will probe the nature of black holes. *International X-ray Observatory* (IXO)—a powerful X-ray telescope that will transform our understanding of hot gas associated with stars and galaxies in all evolutionary stages. (Medium-scale, in rank order) *New Worlds Technology Development Program*—a competed program to lay the technical and scientific foundation for a future mission to study nearby Earth-like planets. *Inflation Probe Technology Development Program*—a competed program designed to prepare for a potential next-decade cosmic microwave-background mission to study the epoch of inflation.

- ***On the Ground:*** (Large-scale, in priority order) *Large Synoptic Survey Telescope* (LSST)—a wide-field optical survey telescope that will transform observation of the variable universe and will address broad questions that range from indicating the nature of dark energy to determining whether there are objects that may collide with Earth. *Mid-Scale Innovations Program augmentation*—a competed program that will provide the capability to respond rapidly to scientific discovery and technical advances with new telescopes and instruments. *Giant Segmented Mirror Telescope* (GSMT)—a large optical and near-infrared telescope that will revolutionize astronomy and provide a spectroscopic complement to the James Webb Space Telescope (JWST), the Atacama Large Millimeter/submillimeter Array (ALMA), and LSST. *Atmospheric Čerenkov Telescope Array* (ACTA)—participation in an international telescope to study very high energy gamma rays. (Medium-scale) *CCAT* (formerly the Cornell-Caltech Atacama Telescope)—a 25-meter wide-field submillimeter telescope that will complement ALMA by undertaking large-scale surveys of dust-enshrouded objects.

These major new elements must be combined with ongoing support of the core research program to ensure a balanced program that optimizes overall scientific return. To achieve that return the committee balances the program with a portfolio of unranked smaller projects and augmentations to the core research program, funded by all three agencies. These elements include support of individual investigators, instrumentation, laboratory astrophysics, public access to privately operated telescopes, suborbital space missions, technology development, theoretical investigations, and collaboration on international projects.

This report also identifies unique ways that astronomers can contribute to solving the nation's challenges. In addition, the public will continue to be inspired with images of the cosmos and descriptions of its contents, and students of all ages will be engaged by vivid illustrations of the power of science and technology. These investments will sustain and improve the broad scientific literacy vital to a technologically advanced nation as well as providing spin-off technological applications to society.

The committee notes with appreciation the striking level of effort and involvement in this survey contributed by the astronomy and astrophysics community. The vision detailed in this report is a shared vision.

RECOMMENDED PROGRAM

Maintaining a balanced program is an overriding priority for attaining the overall science objectives that are at the core of the program recommended by the survey committee. More detailed guidance is provided in the report, but optimal implementation is the responsibility of agency managers. The small-scale projects recommended in Table ES.1 are unranked and are listed in alphabetical order. The highest-priority ground-based elements in the medium (Table ES.2) and large (Table ES.3) categories are listed in priority order, and the highest-priority space-based elements in the medium (Table ES.4) and large (Table ES.5) categories are also listed in priority order. All cost appraisals are in FY2010 dollars.

TABLE ES.1 Space and Ground: Recommended Activities—Small Scale (Alphabetical Order)

Recommendation	Agency	Science	Budget,[a] 2012-2021	Cross-Reference in Chapter 7
(Augmentation to) Advanced Technologies and Instrumentation	NSF	Broad; key opportunities in advanced instrumentation, especially adaptive optics and radio instrumentation	$5M/year additional	Page 236
(Augmentation to) Astronomy and Astrophysics Research Grants Program	NSF	Broad realization of science from observational, empirical, and theoretical investigations, including laboratory astrophysics	$8M/year additional	Page 236
(Augmentation to) Astrophysics Theory Program	NASA	Broad	$35M additional	Page 219
(Definition of) a future ultraviolet-optical space capability	NASA	Technology development benefiting a future ultraviolet telescope to study hot gas between galaxies, the interstellar medium, and exoplanets	$40M	Page 219
(Augmentation to) the Gemini international partnership	NSF	Increased U.S. share of Gemini; science opportunities include exoplanets, dark energy, and early-galaxy studies	$2M/year additional	Page 236
(Augmentation to) Intermediate Technology Development	NASA	Broad; targeted at advancing the readiness of technologies at technology readiness levels 3 to 5	$2M/year additional, increasing to $15M/year additional by 2021	Page 220
(Augmentation to) Laboratory Astrophysics	NASA	Basic nuclear, ionic, atomic, and molecular physics to support interpretation of data from JWST and future missions	$2M/year additional	Page 220
(U.S. contribution to JAXA-led) SPICA mission	NASA	Understanding the birth of galaxies, stars, and planets; cycling of matter through the interstellar medium	$150M	Page 218
(Augmentation to) the Suborbital Program	NASA	Broad, but including especially cosmic microwave background and particle astrophysics	$15M/year additional	Page 221
(Augmentation to) the Telescope System Instrument Program	NSF	Optical-infrared investments to leverage privately operated telescopes and provide competitive access to U.S. community	$2.5M/year additional	Page 236
Theory and Computation Networks	NASA NSF DOE	Broad; targeted at high-priority science through key projects	$5M/year NASA $2.5M/year NSF $2M/year DOE	Page 222

[a] Recommended budgets are in FY2010 dollars and are committee-generated and based on available community input.

TABLE ES.2 Ground: Recommended Activities—Medium Scale

Recommendation[b]	Science	Technical Risk[c]	Appraisal of Costs Through Construction[a] (U.S. Federal Share, 2012-2021)	Appraisal of Annual Operations Costs[d] (U.S. Federal Share)	Cross-Reference in Chapter 7
CCAT —Science early 2020s —University-led, 33% federal share	Submillimeter surveys enabling broad extragalactic, galactic, and outer-solar-system science	Medium	\$140M (\$37M)	\$11M (\$7.5M)	Page 234

[a] The survey's construction-cost appraisal for CCAT is based on the survey's cost, risk, and technical readiness evaluation (i.e., the cost appraisal and technical evaluation, or CATE, analysis) and project input, in FY2010 dollars.
[b] The survey's appraisal of the schedule to first science is based on CATE analysis and project input.
[c] The risk scale used was low, medium low, medium, medium high, and high.
[d] The survey's appraisal of operations costs, in FY2010 dollars, is based on project input.

TABLE ES.3 Ground: Recommended Activities—Large Scale (Priority Order)

Recommendation[b]	Science	Technical Risk[c]	Appraisal of Costs Through Construction[a] (U.S. Federal Share, 2012-2021)	Appraisal of Annual Operations Costs[d] (U.S. Federal Share)	Cross-Reference in Chapter 7
1. LSST —Science late 2010s —NSF/DOE	Dark energy, dark matter, time-variable phenomena, supernovae, Kuiper belt and near-Earth objects	Medium low	\$465M (\$421M)	\$42M (\$28M)	Page 223
2. Mid-Scale Innovations Program —Science mid-to-late 2010s	Broad science; peer-reviewed program for projects that fall between the NSF MRI and MREFC limits	N/A	\$93M to \$200M		Page 225
3. GSMT —Science mid-2020s —Immediate partner choice for ~25% federal share	Studies of the earliest galaxies and galactic evolution; detection and characterization of planetary systems	Medium to medium high	\$1.1B to \$1.4B (\$257M to \$350M)	\$36M to \$55M (\$9M to \$14M)	Page 228

continued

TABLE ES.3 Continued

Recommendation[b]	Science	Technical Risk[c]	Appraisal of Costs Through Construction[a] (U.S. Federal Share, 2012-2021)	Appraisal of Annual Operations Costs[d] (U.S. Federal Share)	Cross-Reference in Chapter 7
4. ACTA —Science early 2020s —NSF/DOE; U.S. join European Čerenkov Telescope Array	Indirect detection of dark matter; particle acceleration and active galactic nucleus science	Medium low	$400M ($100M)	Unknown	Page 232

[a] The survey's construction-cost appraisals for the Large Synoptic Survey Telescope (LSST), Giant Segmented Mirror Telescope (GSMT), and Atmospheric Čerenkov Telescope Array (ACTA) are based on the survey's cost, risk, and technical readiness evaluation (i.e., the cost appraisal and technical evaluation, or CATE, analysis) and project input, in FY2010 dollars; cost appraisals for the Mid-Scale Innovations Program augmentation are committee-generated and based on available community input. For GSMT the cost appraisals are $1.1 billion for the Giant Magellan Telescope (GMT) and $1.4 billion for the Thirty Meter Telescope (TMT). Construction costs for GSMT could continue into the next decade, at levels of up to $95 million for the federal share. The share for the U.S. government is shown in parentheses when it is different from the total.

[b] The survey's appraisals of the schedule to first science are based on CATE analysis and project input.

[c] The risk scale used was low, medium low, medium, medium high, and high.

[d] The contractor had no independent basis for evaluating the operations cost estimates provided for any ground-based project. The survey's appraisals for operations costs, in FY2010 dollars, were constructed by the survey committee on the basis of project input and the experience and expertise of its members. For GSMT the range in operations costs is based on estimates from GMT ($36 million) and TMT ($55 million). The share for the U.S. government is shown in parentheses when it is different from the total.

TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]	Cross-Reference in Chapter 7
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M	Page 215
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M	Page 217

[a] The survey's cost appraisals are in FY2010 dollars and are committee-generated and based on available community input.

TABLE ES.5 Space: Recommended Activities—Large-Scale (Priority Order)

Recommendation	Launch Date[b]	Science	Technical Risk[c]	Appraisal of Costs[a]: Total (U.S. Share)	Appraisal of Costs[a]: U.S. Share, 2012-2021	Cross-Reference in Chapter 7
1. WFIRST —NASA/DOE collaboration	2020	Dark energy, exoplanets, and infrared survey-science	Medium low	$1.6B	$1.6B	Page 205
2. Augmentation to Explorer Program	Ongoing	Enable rapid response to science opportunities; augments current plan by 2 Medium-scale Explorer (MIDEX) missions, 2 Small Explorer (SMEX) missions, and 4 Missions of Opportunity (MoOs)	Low	$463M	$463M	Page 208
3. LISA —Requires ESA partnership[d]	2025	Open low-frequency gravitational-wave window for detection of black-hole mergers and compact binaries and precision tests of general relativity	Medium[e]	$2.4B ($1.5B)	$852M	Page 209
4. IXO —Partnership with ESA and JAXA[d]	2020s	Black-hole accretion and neutron-star physics, matter/energy life cycles, and stellar astrophysics	Medium high	$5.0B ($3.1B)	$200M	Page 213

[a] The survey's cost appraisals for Wide-Field Infrared Survey Telescope (WFIRST), Laser Interferometer Space Antenna (LISA), and International X-ray Observatory (IXO) are based on the survey's cost, risk, and technical readiness evaluation (i.e., the cost appraisal and technical evaluation, or CATE, analysis) and project input, in FY2010 dollars for phase A costs onward; cost appraisals for the Explorer augmentation and the medium elements of the space program are committee-generated, based on available community input. The share for the U.S. government is shown in parentheses when it is different from the total. The U.S. share is based on the United States assuming a 50 percent share of costs and includes an allowance for extra costs incurred as a result of partnering.

[b] The survey's appraisal of the schedule to launch is the earliest possible based on CATE analysis and project input.

[c] The risk scale used was low, medium low, medium, medium high, and high.

[d] Note that the LISA and IXO recommendations are linked—both are dependent on mission decisions by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA).

[e] Technical risk assessment of "medium" is contingent on a successful LISA Pathfinder mission.

1

2020 Vision

The universe has always beckoned us. Over the course of human civilization, the night sky has provided a calendar for the farmer, a guide for the sailor, and a home for the gods. Astronomy led the scientific revolution, which continues to this day and has revealed that the sky visible to the naked eye is really just a hint of a vast and complex cosmos, within which our home planet is but a pale blue dot. Astronomers continue to explore the universe, learning its amazing history, discovering the richness of its contents, and understanding the physical processes that take place in its astoundingly diverse environments. Today, astronomy expands knowledge and understanding, inspiring new generations to ask, How did the universe form and the stars first come into being? Is there life beyond Earth? What natural forces control our universal destiny?

Because of the remarkable scientific progress in recent decades, in particular the explosion over the last decade of interest in and urgency to understand several key areas in astronomy and astrophysics, scientists are now poised to address these and many other equally profound questions in substantive ways. These dramatic discoveries came about through the application of modern technology and human ingenuity to the ancient craft of observing the sky. We have explored the cosmos, not just by observing through the tiny visible window used by our eyes, but also by exploiting the entire electromagnetic spectrum, from radio waves with wavelengths larger than a house to gamma rays with wavelengths 1,000 times smaller than a proton. The universe has also been studied by using samples returned to Earth from comets and meteorites, and by detecting and analyzing high-energy particles that permeate space. The opportunities for the future fill us with awe, enrich our culture, and frame our view of the human condition.

This report is the result of the National Research Council's (NRC's) survey of astronomy and astrophysics for the decade of the 2010s—Astro2010. The survey covers what has been learned, what could be learned, and what it will take to sustain the current revolution in understanding. As requested, the report outlines a plan to realize the scientific promise of the decade to come. The recommended major new elements must be combined with ongoing support for and augmentation of the foundational core of the federally supported research program to ensure a balanced program in astronomy and astrophysics that optimizes overall scientific return.

Below and in subsequent chapters of this report the Committee for a Decadal Survey of Astronomy and Astrophysics presents a compelling science program (Chapter 2), outlines the relationship of the federal program to the larger astronomy and astrophysics enterprise (Chapters 3 and 4), discusses workforce development and other core activities (Chapters 5 and 6), and describes in detail the integrated program it recommends for the decade ahead (Chapter 7). The process that was followed in carrying out Astro2010 is recounted in this report's preface and reviewed again in Chapter 7.

SCIENCE OBJECTIVES

The exciting program of activities proposed here will help to advance understanding of how the first galaxies formed and started to shine. It will direct the discovery of the closest habitable planets beyond our solar system. It will use astronomical measurements to try to unravel the mysteries of gravity and will probe fundamental physics beyond the reach of Earth-based experiments. The committee found that the way to optimize the science return for the decade 2012-2021 within the anticipated resources was to focus on these three science objectives while also considering the discovery potential of a much broader research program. To achieve these objectives, a complementary effort of space-based, ground-based, and foundational, core research is required.

Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes

We have learned much in recent years about the history of the universe, from the big bang to the present day. A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our "cosmic dawn"? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization. Scientists think that the first stars were massive and short-lived. They quickly exploded as supernovae, creating and dispersing the first elements with nuclei heavier than those of hydrogen, helium, and lithium, and leaving behind the first black holes. Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings.

After the cosmic dawn, more and more galaxies formed, merged, and evolved as their gas turned into stars and those stars aged. Many of the faintest images from current telescopes are of these growing infant galaxies. Their properties are just starting to be revealed. In particular, it is now known that such galaxies quickly grow black holes in their nuclei with masses that can exceed a billion times the mass of the Sun and become extraordinarily luminous quasars. How this happens is a mystery.

We also know that the giant galaxies we see around us today were built up from the mergers of smaller galaxies and the accretion of cold gas. Not only do the stars and gas commingle, but the central black holes also merge. Amazingly, it should be possible to detect waves in the fabric of space-time—gravitational waves—that result from the dramatic unions when galaxies and black holes are young and relatively small.

Another approach to understanding our cosmic dawn is to carry out "cosmic paleontology" by finding the rare stars that have the lowest concentrations of heavy elements and were formed at the earliest times. Today, we can scrutinize only stars in our galaxy; in the future, we will be able to explore other nearby galaxies to uncover stellar fossils and use them to reconstruct the assembly of young galaxies.

Exploring the first stars, galaxies, and quasars is a tremendous challenge, but one astronomers and astrophysicists are ready to tackle and overcome, thereby continuing the story of how our universe came to be.

New Worlds: Seeking Nearby, Habitable Planets

On Christmas Eve, 1968, Apollo 8 astronaut William Anders took an iconic photograph of the rising Earth from his vantage point orbiting the Moon. It highlighted, to more people than ever before, that we humans share a common home that is both small and fragile. It also brought into focus the question, What does Earth look like from much farther away? Remarkable discoveries over the past 15 years have led us to the point that we can ask and hope to answer the question, Can we find another planet like Earth orbiting a nearby star? To find such a planet would complete the revolution, started by Copernicus nearly 500 years ago, that displaced Earth as the center of the universe.

Almost two decades ago, astronomers found evidence for planets around neutron stars, and then, in 1995, a star just like the Sun in the constellation Pegasus was shown to vary regularly in its radial velocity—resulting from motion toward or away from us here on Earth—in response to the gravitational pull of an orbiting planet. This planet was roughly as massive as Jupiter but orbited its star every 4 days, far more quickly than any of our Sun's planets. So, in a single set of observations we solved an age-old puzzle: yes, there are other planetary systems around stars like our Sun. However, they do not necessarily look like our solar system. Today, in mid-2010, we know of almost 500 extrasolar planets with masses ranging from a few to a few thousand times the mass of Earth.

We have greatly expanded our discovery techniques since 1995. Radial velocity detection of planets is much more sensitive, reaching down below 10 Earth masses. We can detect tiny changes in the combined light of a star and planet as they transit in front of one other, a technique currently being exploited very successfully by the Kepler space telescope. We can also probe planetary systems by measuring microlensing as their gravitational fields bend rays of light from a more distant star. Telescopes on the ground and in space have even directly imaged as distinct point sources a few large planets. In other cases, we can learn about planetary systems by measuring infrared and radio emission from giant disks of gas out of which planets can form. Finally, in a most important development, the Hubble Space Telescope and the Spitzer Space Telescope have found the spectral lines of carbon dioxide, water, and the first organic molecule, methane, in the atmospheres of orbiting planets. This is extraordinarily rapid progress.

Astronomers are now ready to embark on the next stage in the quest for life beyond the solar system—to search for nearby, habitable, rocky or terrestrial planets with liquid water and oxygen. The host star of such a planet may be one like our Sun, or it could be one of the more plentiful but less hospitable cooler red stars. Cooler red stars are attractive targets for planet searches because light from a planet will be more easily detected above the stellar background. Making the search harder, terrestrial planets are relatively small and dim, and are easily lost in the exozodiacal light that is scattered by the dusty disks that typically orbit stars. The observational challenge is great, but armed with new technologies and advances in understanding of the architectures of nearby planetary systems, astronomers are poised to rise to it.

Physics of the Universe: Understanding Scientific Principles

Astronomy and physics have always been closely related. Observations of orbiting planets furnished verifications of Newton's law of gravitation and Einstein's theory of gravity—general relativity. In more recent years, observations of solar system objects and radio pulsars have provided exquisitely sensitive proof that general relativity is, indeed, correct when gravity is weak. The universe continues to be a laboratory that offers access to regimes not available on Earth, helping us to both understand and discover new elements of the basic laws of nature.

Scientists can study the universe on the largest observable scales—more than 10 trillion, trillion times larger than the size of a person. The past decade has seen the confirmation from measurements of the truly remarkable discovery that the expansion of the universe is accelerating. In modern language, this acceleration is attributed to the effect of a mysterious substance called dark energy that accounts for 75 percent of the mass-energy of the universe today causing galaxies to separate at ever faster speeds. The remainder of the mass-energy is 4.6 percent regular matter and 20 percent a new type of matter, dubbed dark matter, that is believed to comprise new types of elementary particles not yet found in terrestrial laboratories. The effects of dark energy are undetectable on the scale of an experiment on Earth. The only way forward is to use the universe at large to infer the properties of dark energy by measuring its effects on the expansion rate and the growth of structure.

Amazingly, we can ask and hope to answer questions about the universe as it was very soon after the big bang. Recent observations of the microwave background are consistent with the theory that the universe underwent a burst of inflation when the expansion also accelerated and the scale of the universe that we see today grew from its infinitesimally small beginnings to about the size of a fist. Gravitational waves created at the end of the epoch of inflation can propagate all the way to us and carry information about the behavior of gravity and other forces during the first moments after the big bang. These waves can be detected through the distinctive polarization pattern[1] that they impose on the relic cosmic microwave background radiation. Detection of this imprint would both probe fundamental physics at very high energies and bear witness to the birth of the universe.

Yet another opportunity to study fundamental principles comes from precisely observing the behavior of black holes. Black holes are commonly found in the nuclei of normal galaxies and are born when very massive stars end their stellar lives. Scientists have an exact theoretical description of space-time around black holes but do not know if this description is correct. One way to find out is to observe X-ray-emitting gas and stars as they spiral toward a black hole's event horizon beyond which nothing, not even light, can escape. Another is to observe the jets that escape black holes with speeds close to that of light. However, the best test of all will come from measuring the gravitational radiation that is observed when moderate-mass black holes merge. We now have the software and the computing power to calculate the signals that should be seen and the technology to test the theory.

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[1] The cosmic microwave radiation signal can be decomposed into two components: an E-mode and a B-mode. Patterns in these polarization modes allow determination of conditions when the radiation was emitted.

What excites astronomers and physicists alike is that the tools are now at hand to greatly expand current understanding of fundamental physics in new and important ways.

OPTIMIZING THE SCIENCE PROGRAM

Astronomy is a rich and diverse science that encompasses much more than the grand challenges described above. There are great opportunities to be seized over a broad research program, as described in Chapter 2. Astronomy is still driven by discovery, and when the programs described in past decadal surveys were successfully executed, many of the most important results were largely unanticipated. The new facilities contained in this survey's recommended program are highly versatile. In addition to carrying out the observational program described, they will advance the broad research program and are also able to both make and respond to fresh breakthroughs.

This report is written at a time when the nation's finances are severely stressed. The committee was charged to consider alternative budget scenarios. It chose to adopt for each agency the agency-projected budget and a second, optimistic budget that reflects modest relative growth. In the case of the National Aeronautics and Space Administration (NASA), the agency-projected budget is flat in real-year dollars and allows very little new activity until the James Webb Space Telescope (JWST) is launched, presumably in mid-decade. The optimistic budget used by the committee is flat in FY2010 dollars. In the case of the National Science Foundation (NSF), the agency-projected budget is flat in FY2010 dollars, which allows little to no opportunity for new activity over the entire decade, given the obligations to support existing facilities. The optimistic budget used by the committee supposes growth in purchasing power at a rate of 4 percent per year, the so-called doubling scenario that is being applied to the overall NSF budget. In the case of the Department of Energy (DOE), the agency-projected budget is constant in FY2010 dollars, and the optimistic budget used by the committee is also on a doubling track, consistent with the current administration's stated policy for the DOE Office of Science. The committee's recommended program that follows has been constrained to fit under the optimistic budget envelopes. Reductions that would be needed under less favorable budgets are also described.

A successful federal research program must also be balanced. There is a tradeoff between investing in the development and construction of ambitious new telescopes and supporting broad-ranging observational and theoretical research that optimizes the return from operating facilities. The goal of the committee, consistent with its charge, has been to maximize the science return for a given budget. The committee found that in some cases the balance of resources is not optimal, and this report contains a number of recommendations to augment or adjust the foundations of the program.

The committee's proposed program (Chapter 7) is recommended on the basis of four general criteria—maximizing scientific contribution, building on the current astronomy and astrophysics enterprise, balancing this decade's programs against investing in the next decade's, and optimizing the science return given the highly constrained budget. These criteria are discussed further below. The resulting program emphasizes certain capabilities for U.S. leadership, including all-sky synoptic imaging on the ground and in space, large-aperture telescopes, exploration of non-electromagnetic portals to the universe, technology and software, public-private and international partnerships, frequent opportunities for new medium-scale instrumentation on the ground and in space, and interdisciplinary work, especially work involving connections between astrophysics and physics.

Finally, a key concern of the committee's is the stewardship of the present survey's recommended program. Although a good-faith attempt has been made to provide answers to all the questions raised by the charge, it is in the very nature of research that unforeseen issues requiring community advice will arise. In addition, there will be a need to monitor progress. Accordingly, implementation of the survey will require stewardship over the coming decade in the form of strategic advice requested by but generated independent of the agencies supporting the field.

RECOMMENDATION: NASA, NSF, and DOE should on a regular basis request advice from an independent standing committee constituted to monitor progress toward reaching the goals recommended in the decadal survey of astronomy and astrophysics, and to provide strategic advice to the agencies over the decade of implementation. Such a decadal survey implementation advisory committee (DSIAC) should be charged to produce annual reports to the agencies, the Office of Management and Budget, and the Office of Science and Technology Policy, as well as a mid-decade review of the progress made. The implementation advisory committee should be independent of the agencies and the agency advisory committees in its membership, management, and operation.

PROPOSED PROGRAM OF ACTIVITIES

The committee's recommended program is presented in terms of specific space-based[2] and ground-based projects and opportunities. In space, large-scale activities are those having a total appraised cost exceeding $1 billion, while medium-scale activities have a total cost estimated to range from $300 million to $1 billion. On the ground, large-scale activities are those whose total cost is appraised to exceed $135 million, while medium-scale activities have a total cost in the range of $4 million to $135 million. All values are in FY2010 dollars.[3]

Space Projects—Large—in Rank Order

Wide-Field Infrared Survey Telescope (WFIRST)

A 1.5-meter wide-field-of-view near-infrared-imaging and low-resolution-spectroscopy telescope, WFIRST will settle fundamental questions about the nature of dark energy, the discovery of which was one of the greatest achievements of U.S. telescopes in recent years. It will employ three distinct techniques—measurements of weak gravitational lensing, supernova distances, and baryon acoustic oscillations—to determine the effect of dark energy on the evolution of the universe. An equally important outcome will be to open up a new frontier of exoplanet studies by monitoring a large sample of stars in the central bulge of the Milky Way for changes in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters. It will also, in guest investigator mode, survey our galaxy and other nearby galaxies to answer key questions about their formation and structure, and the data it obtains will provide fundamental constraints on how galaxies grow. The telescope exploits the important work done

[2] Two space missions recommended in the 2001 NRC decadal survey *Astronomy and Astrophysics in the New Millennium* (AANM; National Academy Press, Washington, D.C.)—namely ARISE and EXIST—and one recommended by the 1991 NRC survey *The Decade of Discovery in Astronomy and Astrophysics* (National Academy Press, Washington, D.C.), SIM, do not appear in this survey's priorities. The goals of ARISE have been largely subsumed by JAXA's VLBI Space Observatory Programme (VSOP)-2 project and the SAMURAI (Science of AGNs and Masers with Unprecedented Resolution in Astronomical Imaging) proposal. EXIST and SIM (now SIMLite) are not included in the recommended program for the decade, following the committee's consideration of the strengths of competing compelling scientific opportunities and the highly constrained budget scenarios described in this report.

[3] All costs are given in FY2010 dollars. A recommendation of level funding is equivalent to a recommendation of constant level of effort. Details on the methodology used to assess cost and schedule risk and technical readiness are provided in Chapter 7 and Appendix C. Cost and schedule risk was assessed relative to project estimates. Technical readiness was assessed independent of cost. The risk scale used was low, medium low, medium, medium high, and high.

by the joint DOE/NASA design team on the Joint Dark Energy Mission—specifically the JDEM-Omega concept—and expands its scientific reach. WFIRST is based on mature technologies with technical risk that is medium low and has medium cost and schedule risk. The independent cost appraisal is $1.6 billion, not including the guest investigator program. As a telescope capable of imaging a large area of the sky, WFIRST will complement the targeted infrared observations of the James Webb Space Telescope. The small field of view of JWST would render it incapable of carrying out the prime WFIRST program of dark energy and exoplanet studies, even if it were used exclusively for this task. The recommended schedule has a launch data of 2020 with a 5-year baseline mission. An extended 10-year mission could improve the statistical results and further broaden the science program. The European Space Agency (ESA) is considering an M-class proposal, called Euclid, with related goals. Collaboration on a combined mission with the United States playing a leading role should be considered so long as the committee's recommended science program is preserved and overall cost savings result.

WFIRST addresses fundamental and pressing scientific questions and will contribute to a broad range of astrophysics. It complements the committee's proposed ground-based program in two key science areas: dark energy science and the study of exoplanets. It is a part of coordinated and synergistic programs in fields in which the United States has pioneered the progress to date. It presents opportunities for interagency and perhaps international collaboration that would tap complementary experience and skills. It also presents relatively low technical and cost risk, making its completion feasible within the decade, even in a constrained budgetary environment. For all these reasons it is the committee's top-priority recommendation for a space mission.

Explorer Program Augmentation

The Explorer program supports small and medium-size missions, selected through competitive peer review, that are developed and launched on roughly 5-year timescales. The Explorer program enables rapid responses to new discoveries and provides platforms for targeted investigations essential to the breadth of NASA's astrophysics program. Explorers have delivered a scientific return on investment at the highest level over the past two decades. The three astrophysics Medium-scale Explorer (MIDEX) missions launched to date—the Wilkinson Microwave Anisotropy Probe (WMAP), Swift, and the Wide-Field Infrared Survey Explorer (WISE)—have provided high-impact science for a combined cost significantly less than that of a single flagship mission.[4] WMAP, launched just 5 years after the

[4] According to NASA the combined development cost (not including operations) for WMAP, Swift, and WISE was $590 million (real year), about 50 percent the cost of a single past NASA Great Observatory.

Cosmic Background Explorer (COBE) discovered that the cosmic microwave background (CMB) has measurable fluctuations, demonstrated that these tiny variations imprint precise information about the early universe. WMAP is credited with obtaining the best measurements of the age, geometry, and content of the universe. The Swift mission has transformed understanding of explosive gamma-ray burst events, and it holds the record for detecting the most distant object in the universe. The WISE mid-infrared survey, extending over the entire sky, is studying the coolest stars, the universe's most luminous galaxies, and some of the dimmest near-Earth asteroids and comets. Small Explorer (SMEX) missions, as well as Mission of Opportunity contributions to non-NASA missions, have made essential advances in understanding of phenomena ranging from the explosive release of energy in flares on the Sun (with the Reuven Ramaty High Energy Solar Spectroscopic Imager) to the assembly of galaxies (with the Galaxy Evolution Explorer). The promise of future Explorer missions is as great as ever, and this program will be essential to enabling new opportunities, and to maintaining breadth and vibrancy in NASA's astrophysics portfolio in a time of budgetary stress. This survey recommends that the annual budget of the astrophysics component of the Explorer program be increased from $40 million to $100 million by 2015.

The categorization of the recommended Explorer program augmentation as a large-category activity reflects the total cost of the augmentation for the decade 2012-2021, and its high ranking is motivated by the committee's view that expanding the Explorer program is a very effective way to maximize scientific progress for a given outlay.

Laser Interferometer Space Antenna (LISA)

LISA employs three separated spacecraft to detect long-wavelength ripples in the fabric of space-time, thereby opening a new window on the universe. LISA will detect the mergers of black holes with masses ranging from 10,000 to 10 million solar masses at cosmological distances, and will make a census of compact binary systems throughout the Milky Way. LISA promises new discoveries as well as progress on central questions such as understanding the growth of galaxies and black holes. LISA will also test general relativity with exquisite precision in regimes inaccessible on Earth. LISA complements the search for gravitational radiation being made at shorter wavelengths by the ground-based Advanced LIGO. LISA is a partnership with ESA, and so its schedule is dependent on ESA's selection of the next L-class mission opportunity—LISA is one of three contenders for this opportunity. LISA's key technologies will be demonstrated on the ESA-led LISA Pathfinder mission, due for launch in 2012. With the success of Pathfinder and a decision by ESA to move forward, LISA could launch by 2025. Independent review found LISA's technical risk, assuming Pathfinder success, to be medium, and the NASA appraised cost, based on a 50 percent participation and including the costs of partnering at such a level, to be \$1.4 billion. The cost and schedule risk classification is medium high. If Pathfinder is not a success or if a roughly equal partnership is not possible, the committee recommends that NASA request advice from a decadal survey implementation advisory committee (DSIAC) to review the situation mid-decade. LISA presents a compelling scientific opportunity, and there is readiness to address its remaining technical challenges.

Overall the recommendation and prioritization for LISA reflect its compelling science case and the relative level of technical readiness.

International X-ray Observatory (IXO)

IXO is a versatile, large-area, high-spectral-resolution X-ray telescope that will make great advances on broad fronts ranging from characterization of black holes to elucidation of cosmology and the life cycles of matter and energy in the cosmos. Central to many of the science questions identified by this survey, IXO will revolutionize high-energy astrophysics with more than an-order-of-magnitude improvement in capabilities. IXO is a partnership among NASA, ESA, and the Japan Aerospace Exploration Agency (JAXA), and, like LISA, it is a candidate for the next L-class ESA launch opportunity. On the basis of a 50 percent participation, it has an appraised cost to NASA, including the cost of partnering, of \$3.1 billion, and the cost and schedule risk is medium high. The technical risk is also medium high. Cost threats and uncertainties due to the immaturity of some of the required technologies have added considerably to the cost appraisal. The budget profiles used by the committee to define an overall program are unlikely to permit a start before the end of the decade—allowing time for the necessary technology maturation and risk reduction. However, this situation does not diminish the committee's assessment of the importance of the discoveries that IXO would make. Because of IXO's high scientific importance, a technology development program is recommended for this decade with sufficient resources—estimated to be on the order of \$200 million—to prepare IXO for favorable consideration in the next survey in 2020. The committee thinks that allowing IXO, or indeed any major mission, to exceed \$2 billion in total cost to NASA would unacceptably imbalance NASA's astrophysics program, given the present budgetary constraints. If the technology development program is not successful in bringing cost estimates below this level, descope options must be considered. Should ESA select IXO as the first L-class mission, NASA should proceed immediately with a DSIAC review to determine an appropriate path forward to realize IXO as soon as possible with acceptable cost and schedule risk.

The ranking of IXO as the fourth-priority large space mission reflects the technical, cost, and programmatic uncertainties associated with the project at the current time. Many high-priority science questions require an X-ray observatory on this scale that can continue the great advances made by Chandra and XMM-Newton. Furthermore, the science of IXO is quite complementary with that of LISA.

Space Projects—Medium—in Rank Order

New Worlds Technology Development Program

One of the fastest-growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone—at a distance from their central star where water can exist in liquid form—and to characterize their atmospheres. To prepare for this endeavor, the committee recommends a program to lay the technical and scientific foundations for a future space imaging and spectroscopy mission. NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates. In the first part of the decade NASA should support competed technology development to advance multiple possible technologies for a next-decade planet imager, and should accelerate measurements of exozodiacal light levels that will determine the size and complexity of such missions. The committee recommends an initial NASA funding level of $4 million per year so as to achieve a clear set of design requirements and technology gateways to be passed. If, by mid-decade, a DSIAC review determines that sufficient information has become or is becoming available on key issues such as planet frequency and exozodiacal dust distribution, a technology down-select should be made and the level of support increased to enable a mission capable of studying nearby Earth-like planets to be mature for consideration by the 2020 decadal survey, with a view to a start early in the 2020 decade. The committee estimates that an additional $100 million will be required for the mission-specific development.

Inflation Probe Technology Development Program

Detecting the distinctive imprint on the cosmic microwave background caused by gravitational waves produced during the first few moments of the universe would provide evidence for the theory of inflation and open a new window on exotic physics in the early universe. Progress in detecting this signal is rapid, with advances from ground-based telescopes, suborbital flights, and the recently launched Planck satellite. The committee recommends a technology program to advance detection techniques at an annual funding level of $1 million to $2 million. If the polarization pattern imprinted by gravitational waves from the epoch of inflation is detected during this decade, the committee recommends a technology selection and mission development to design a mission to study the signal. The resulting proposal would be considered by the 2020 decadal survey. The committee estimates a budget requirement of $60 million for the development, to be triggered in the event of a convincing detection.

Small Additions and Augmentations to Space Research Program (Unranked)

U.S. Contribution to the JAXA-ESA SPICA Mission

The Space Infrared telescope for Cosmology and Astrophysics (SPICA) is a Japanese-led 3.5-meter infrared telescope that will operate from 5 to 210 microns. SPICA will address many of this survey's science priorities, including understanding the birth of galaxies, stars, and planets as well as the motion of matter through our own interstellar medium. A competed U.S. science and instrument contribution at an estimated level of $150 million over the decade is recommended.

Core Research Program

NASA's core research programs, from theoretical studies to innovative technology development, are fundamental to mission development and essential for scientific progress. They provide the long-term foundation for new ideas that stretch the imagination, and they lay the groundwork for far-future vision missions. They support the maturation of new technologies needed for nearer-term Explorer and flagship missions. They provide the means to understand and interpret scientific results. Maintaining these core activities has a high priority for the survey committee, and the budget allocations should not be allowed to decrease to address overruns in the costs of large and medium missions. In addition, the following unranked specific augmentations are recommended.

Astrophysics Theory Program. To enhance the scientific return from operating missions and inform the investment in new ones, an augmentation of $35 million to the current funding level for the decade is recommended.

Definition of a Future Ultraviolet-Optical Space Capability. To prepare for a future major ultraviolet mission to succeed the Hubble Space Telescope, it will be necessary to carry out a mission-definition program. A budget of roughly $40 million over the decade for mission studies and initial technology development is recommended.

Intermediate Technology Development. A gap has emerged within NASA between long-term so-called "Blue Skies" investigations and shorter-term mission-specific technology development. Formally this gap is associated with technology readiness levels 3 to 5. An augmentation beginning at $2 million per year and increasing to $15 million per year by the end of the decade would address this imbalance.

Laboratory Astrophysics. Herschel, JWST, SPICA, and IXO, with their fine spectral capabilities, will place new demands on basic nuclear, ionic, plasma, atomic, and molecular astrophysics. Care should be taken to ensure that these needs are met. An increase by $2 million per year in the funding of the present program is recommended.

Suborbital Program. The balloon and sounding rocket programs provide fast access to space for substantive scientific investigations and flight testing of new technology. The balloon program in particular is important for advancing detection of the cosmic microwave background and particle detection. These programs also provide a training ground for the principal investigators of tomorrow's major missions. A growth in the budget by $15 million per year is recommended.

Theory and Computation Networks. To enable the large-scale theoretical investigations identified as science priorities by this survey, the committee proposes a new competed program to support coordinated theoretical and computational research—particularly that of fundamental relevance to upcoming space observatories. For NASA an annual budget of $5 million is recommended. For DOE an annual funding level of $1 million is recommended for activities related to space-based research.

Ground Projects—Large—in Rank Order

Large Synoptic Survey Telescope (LSST)

LSST is a multipurpose observatory that will explore the nature of dark energy and the behavior of dark matter, and will robustly explore aspects of the time-variable universe that will certainly lead to new discoveries. LSST addresses a large number of the science questions highlighted in this report. An 8.4-meter optical telescope to be sited in Chile, LSST will image the entire available sky every 3 nights. Over a 10-year lifetime, LSST will be a unique facility that, building on the success of the Sloan Digital Sky Survey, will produce a 100-billion-megabyte publicly accessible database. The project is relatively mature in its design. The appraised construction cost is $465 million, two-thirds of which the committee recommends be borne by NSF through its Major Research Equipment and Facilities Construction (MREFC) line and a quarter by DOE using Major Item of Equipment (MIE) funds, with the remaining fraction coming from international and private partners. The annual operations costs are estimated at $42 million, of which $28 million is recommended to be split between NSF and DOE at two-thirds and one-third, respectively. The committee recommends that LSST be submitted immediately for NSF's MREFC consideration with a view to achieving first light before the end of the decade. Independent review judged the cost and schedule risk, as well as the technical risk, to be medium low.

The top rank accorded to LSST is a result of (1) its compelling science case and capacity to address so many of the science goals of this survey and (2) its readiness for submission to the MREFC process. LSST was judged by its technical maturity, the survey's assessment of risk, and appraised construction and operations costs. Having made considerable progress in terms of its readiness since the 2001 survey, LSST was judged as the most "ready-to-go."

Mid-Scale Innovations Program

New discoveries and technical advances enable small- to medium-scale experiments and facilities that advance forefront science. A large number of compelling proposed research activities submitted to this survey were highly recommended by the Program Prioritization Panels, with costs ranging between the limits of the NSF Major Research Instrumentation and MREFC programs, $4 million to $135 million. The committee recommends a new competed program to significantly augment the current levels of NSF support for mid-scale programs. An annual funding level of $40 million per year is recommended—just over double the amount currently spent on projects in this size category through a less formal programmatic structure.

The principal rationale for the committee's ranking of the Mid-Scale Innovations Program is the many highly promising projects for achieving diverse and timely science.

Giant Segmented Mirror Telescope (GSMT)

Transformative advances in optical and infrared (OIR) astronomy are now possible by building adaptive optics telescopes with roughly 10 times the collecting area and up to 80 times the near-infrared sensitivity of current facilities. These observatories will have enormous impact across a large swath of science and will greatly enhance the research that is possible with several other telescopes, especially JWST, the Atacama Large Millimeter/submillimeter Array (ALMA), and LSST. A federal investment to provide access for the entire U.S. astronomy and astrophysics community to an optical-infrared 30-meter-class adaptive optics telescope is strongly recommended. Two U.S.-led projects, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), are being developed by international collaborations led by U.S. private consortia. The committee recommends that a choice between the two projects be made as soon as possible for a federal partnership at a level of about a 25 percent investment in one of them. A schedule and budget plan should then be developed. The survey appraises a total GSMT construction cost in the range of $1.1 billion (GMT appraisal) to $1.4 billion (TMT appraisal) and assumes that the federal share of the capital cost will be borne by MREFC, while recognizing that the total share may be secured through whatever combination of capital cost, operating funds, and instrumentation support is most favorable. The operations federal cost share is expected to carried by NSF-Astronomy. Both telescope projects estimated their annual operations costs (including facility and instrument upgrades) at around $50 million ($36 million, GMT; $55 million, TMT). Although the committee did not analyze these estimates in detail, they are far below the usual rule of thumb for large projects (10 percent of construction costs per year).

The committee believes that a GSMT will, as large telescopes have in the past, transform U.S. astronomy because of the telescope's broad and powerful scientific reach, and that federal investment in a GSMT is vital to U.S. competitiveness in ground-based optical astronomy over the next two decades. These are the main reasons for the committee's strong recommendation of GSMT.

The third-place ranking also results from the requirement in the committee's charge that the survey's prioritization be informed not only by scientific potential but also by the technical readiness of the components and the system, the sources of risk, and the appraisal of costs. LSST and several of the concatenation of candidates for the Mid-Scale Innovations Program were deemed to be ahead of GSMT in these areas. The committee also took into account programmatic concerns such as the time it will take to implement the committee's recommendation for a choice to be made on which one of the two U.S.-led GSMT concepts NSF will partner, and the time it would take for any MREFC decision to be made and federal funds awarded. The committee's setting of the relative positions of its top three ranked activities resulted from its consideration of all these various factors.

Atmospheric Čerenkov Telescope Array (ACTA)

The past decade has seen the coming of age of very high energy tera-electron-volt (TeV) gamma-ray astronomy. Plans are underway to capitalize on recent scientific advances by building a large facility that uses light created as gamma rays interact with the atmosphere and that will achieve an order-of-magnitude greater sensitivity compared to current telescopes. This new gamma-ray observatory will detect a wide variety of high-energy astrophysical sources and seek indirect evidence for dark matter annihilation. Two facilities, the European Čerenkov Telescope Array (CTA) and the U.S. Advanced Gamma-ray Imaging System (AGIS), have been proposed. The survey appraised the full AGIS project cost to be in the $400 million range. The technical risk was judged to be medium low. The committee recommends that the U.S. AGIS team collaborate as a partner with the European CTA team and that a U.S. budget for construction and operations of approximately $100 million over the decade be shared between DOE, NSF-Physics, and NSF-Astronomy.

The recommendation for ongoing U.S. involvement in TeV astronomy is based largely on the demonstrated recent accomplishments of this field and the prospect of building fairly quickly a much more capable facility to address a broad range of astronomy and physics questions over the next decade.

Ground Project—Medium

CCAT

CCAT (formerly the Cornell-Caltech Atacama Telescope) is a powerful wide-field-of-view 25-meter telescope to be constructed at a high site in Chile just above the ALMA site. CCAT will perform sensitive millimeter and submillimeter imaging surveys of large fields, enabling studies of galaxies, stars, planets, and interstellar gas, as well as objects in the outer solar system. CCAT will complement ALMA by finding many of the sources that ALMA will follow up. The committee appraises the total development and construction cost at $140 million. The estimated start of operations is 2020, and the survey judges the cost and schedule risk, and technical risk, as medium. The committee recommends NSF support for the construction costs, on the order of $37 million, and a $7.5 million share of the operations costs, provided that the U.S. community has appropriate access to both the results of the surveys and competed observing time.

CCAT is called out to progress promptly to the next step in development because of its strong science case, its importance to ALMA, and its readiness.

Small Additions and Augmentations to Ground Research Program (Unranked)

Advanced Technologies and Instrumentation (ATI)

ATI supports instrumentation and technology development, including computing at astronomical facilities in support of the research program. The current level of funding is roughly $10 million per year, which the committee proposes to increase to $15 million per year to accommodate key opportunities, including, especially, adaptive optics development and radio instrumentation.

Astronomy and Astrophysics Research Grants Program (AAG)

Individual investigator grants provide critical support for astronomers to conduct the research for which the observatories and instruments are built. The current funding level has fluctuated, especially due to the welcome injection of ARRA[5] funding, but the rough baseline is $46 million. An increase of $8 million to bring the baseline to $54 million is recommended. This increase should include the support of new opportunities in Laboratory Astrophysics.

Gemini Augmentation

The imminent withdrawal of the United Kingdom (UK) from the Gemini partnership will require that additional support come from the remaining partners. Set against this need is a desire to operate the telescopes more efficiently and a belief that cost savings are achievable. An augmentation of $2 million in the annual budget is recommended subject to the results of negotiations between the Gemini Board and NSF.

Telescope System Instrument Program (TSIP)

TSIP supports telescope instrumentation on privately operated telescopes in exchange for observing time. It is a vital component of the OIR system that was instituted following a recommendation of the 2001 decadal survey, AANM. It is currently supporting research at a rate of $2 million to $3 million per year, and an increment to $5 million per year is proposed.

Theory and Computation Networks

This is a new competed program coordinated between NSF and DOE to support coordinated theoretical and computational attacks on selected key projects that are judged ripe for such attention. An NSF annual funding level of $2.5 million is recommended. For DOE an annual funding level of $1 million is recommended. A similar program is proposed for NASA and DOE above in the space-based program recommendations.

OTHER CONCLUSIONS AND RECOMMENDATIONS

The field of astronomy is far more than telescopes and discoveries. It involves people—students for whom it provides a gateway to all science and technology, members of the public who share a fascination with learning about the universe, and astronomers themselves. Within the United States, it involves three science agencies, DOE, NASA, and NSF, and many individuals and private foundations that have generously supported the field in the past and promise to do so in the future.

[5] American Recovery and Reinvestment Act of 2009, commonly referred to as the stimulus act.

Beyond the U.S. astronomy community is a vast network of researchers, facilities, and plans that interface in complex ways, sometime competitively, but increasingly collaboratively. Each of these expressions of the field of astronomy raises policy issues that are also encompassed by the charge to the committee and are mentioned below and discussed in detail in Chapters 3 through 6. The major conclusions and recommendations offered in those chapters are discussed below.

Partnership in Astronomy and Astrophysics Research

The opportunities described in the reports from the survey's Program Prioritization Panels on optical and infrared and on radio, millimeter, and submillimeter astronomy from the ground; on electromagnetic observations from space; and on particle astrophysics and gravitation are compelling. Having reviewed so many opportunities for building research facilities and instruments that would be dependent on multiple approaches to collaborative science, the committee was easily convinced of the value of a continued emphasis on forging new and strong partnerships.

CONCLUSION: Complex and high-cost facilities are essential to major progress in astronomy and astrophysics and typically involve collaboration of multiple nations and/or collaboration of federal and non-federal institutions. These partnerships bring great opportunities for pooling resources and expertise to fulfill scientific goals that are beyond the reach of any single country. However, they also present management challenges and require a new level of strategic planning to bring them to fruition.

International Collaboration

Dramatic discoveries about the universe have stimulated a substantial growth of interest in astronomy, in other countries and in allied disciplines like physics. Although the federal investment in astronomy has increased, that of the rest of the world has grown much faster. Astronomical research is becoming a more international enterprise. Almost all new major facilities involve scientists and engineers from all around the world and are built and operated with funds from diverse sources. These changes necessitate new approaches to providing access and sharing data that are both more flexible and more equitable.

RECOMMENDATION: U.S. investors in astronomy and astrophysics, both public and private, should consider a wide range of approaches to realize participation in international projects and to provide access for the U.S. astronomy and astrophysics community to a larger suite of facilities than

can be supported within the United States. The long-term goal should be to maximize the scientific output from major astronomical facilities throughout the world, a goal that is best achieved through opening access to all astronomers.

International Strategic Planning

Another consequence of the globalization of astronomy is that it no longer suffices to make national strategic plans. Indeed, much of the challenge of the present survey derives from this realization. It is neither realistic nor advisable to imagine creating a single international strategic plan that separates the science from the funding authority. However, a regular comparison of national and, in the case of Europe, continental plans can provide a forum for reviewing developments in science and technology and can create a fertile environment where successful collaborations can grow. One large international project for which such a forum would be beneficial is the Square Kilometer Array (SKA). Despite the unqualified enthusiasm for the science that this facility could deliver and the recognition that it represents the long-term future of radio astronomy, the committee encountered a major discrepancy between the schedule advertised by the international SKA community and the timescale on which NSF could realistically make a significant contribution to SKA's construction and operations costs.

RECOMMENDATION: Approximately every 5 years the international science community should come together in a forum to share scientific directions and strategic plans, and to look for opportunities for further collaboration and cooperation, especially on large projects.

Society, Astronomy, and Astronomers

Serving the Nation

The committee's recommended ambitious program of research in astronomy and astrophysics is driven in part by the benefits to society. Although the impetus for public support for the astronomy and astrophysics research enterprise will always be primarily the quest for an ever-deepening knowledge of our universe, as discussed elsewhere in this report that public support also produces significant additional benefits for the nation and its people.

CONCLUSION: Astronomy is a pure science, driven by human curiosity. Nevertheless, the techniques and models developed in the process of conducting astronomical research often have broad utility. For example, advances in

understanding of the Sun and of the climates of other planets help illuminate critical issues and inform thinking about climate change here on Earth. The impact of recent discoveries and the many new opportunities thus created have led to great interest in astronomy.

The urgency for federal investment in science, technology, engineering, and mathematics (STEM) education and research was highlighted in the influential 2007 National Academies report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*.[6]

CONCLUSION: Astronomical research continues to offer significant benefits to the nation beyond astronomical discoveries. These benefits include its role in capturing the public's attention and thereby promoting general science literacy and proficiency, its service as a gateway to science, technology, engineering, and mathematics careers, and a number of important and often unexpected technological spin-offs. The field of astronomy and astrophysics deserves inclusion in initiatives to enhance basic research, such as the America COMPETES Act.

As further service to the nation, important roles in government can be played by suitably skilled scientists. Not only are they able to inform the decision-making process, but they also can develop a rare appreciation of the challenges of the political process, which they are well-placed to communicate to other scientists.

RECOMMENDATION: The astronomical community should encourage and support astronomers' commitment to serve in science service/policy positions, on a rotator, fellowship, or permanent basis, at the relevant funding agencies—NSF, NASA, DOE—in Congress, at the Office of Management and Budget, or at the Office of Science and Technology Policy.

Career Planning

A consequence of the current excitement in the field of astronomy is that it attracts many highly capable students who contribute substantially to the research enterprise. Not all of these will take up long-term positions in astronomy, and so it is fortunate that training in astronomical research appears to be well matched in practice to much broader career opportunities. However, the situation also appears to be changing rapidly, and there is a need for students and postdoctoral scholars to be responsibly informed about their employment options on the basis of reliable

[6] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, The National Academies Press, Washington, D.C., 2007.

and current information. There is a particular need to educate and expose young researchers to issues of public policy.

RECOMMENDATION: The American Astronomical Society and the American Physical Society, alongside the nation's astronomy and astrophysics departments, should make both undergraduate and graduate students aware of the wide variety of rewarding career opportunities enabled by their education, and be supportive of students' career decisions that go beyond academia. These groups should work with the federal agencies to gather and disseminate demographic data on astronomers in the workforce to inform students' career decisions.

Underrepresented Groups

By all measures minority Americans are seriously underrepresented among professional astronomers, and women have not yet achieved parity. For many reasons, improving the involvement of minority Americans and women is a matter of the highest priority. As discussed in Chapter 4, the committee came to the following two conclusions:

CONCLUSION: Little progress has been made in increasing the number of minorities in astronomy. Agencies, astronomy departments, and the community as a whole need to refocus their efforts on attracting members of underrepresented minorities to the field.

CONCLUSION: The gender gap in astronomy has diminished significantly, although women still occupy only a small percentage of the most senior positions. Astronomy departments and the community as a whole need to continue work to promote gender equity at all levels.

Sustaining Core Capabilities

Theory

The role of theorists has changed greatly in recent times, and they have become more engaged in the interpretation of current data as well as the planning of future facilities and missions. In addition, computational approaches have expanded greatly the range of problems that can be solved with confidence. The committee concluded that a new approach to supporting theory is needed, a conclusion that is reflected in its proposed program.

RECOMMENDATION: A new program of Research Networks in Theoretical and Computational Astrophysics should be funded by DOE, NASA, and NSF. The program would support research in six to eight focus areas that cover major theoretical questions raised by the survey's Science Frontiers Panels.

Data Handling

A related issue is the increasing importance of data handling in astronomical projects and the need to see data analysis as an integral part of any new project. In the committee's view the best proposals for new major ground-based facilities and instruments include such planning.

RECOMMENDATION: Proposals for new major ground-based facilities and instruments with significant federal funding should be required as a matter of agency policy to include a plan and if necessary a budget for ensuring appropriate data acquisition, processing, archiving, and public access after a suitable proprietary period.

Data Curation

Many astronomical data sets have long-term value and benefits. The committee concluded that there is a need for attention to data curation.

RECOMMENDATION: NSF, NASA, and DOE should plan for effective long-term curation of, and access to, large astronomical data sets after completion of the missions or projects that produced these data, given the likely future scientific benefit of the data. NASA currently supports widely used curated data archives, and similar data curation models could be adopted by NSF and DOE.

Laboratory Astrophysics

Another important component of the astrophysical infrastructure is the ability to carry out crucial measurements in the laboratory that are relevant to interpreting observations from astronomical environments. The suite of recently launched and proposed facilities will make the acquisition of laboratory data even more crucial than it has been in the past.

CONCLUSION: DOE national laboratories, including those funded by the Office of Science and the National Nuclear Security Administration, have many unique facilities that can provide basic astrophysical data.

The committee believes that NASA, NSF, and DOE will need to include funding for laboratory astrophysics in support of new missions and facilities and supports this conclusion in its proposed program. Other funding models should be considered if it is deemed necessary and cost-effective.

RECOMMENDATION: NASA and NSF support for laboratory astrophysics under the Astronomy and Physics Research and Analysis and the Astronomy and Astrophysics Research Grants programs, respectively, should continue at current or higher levels over the coming decade because these programs are vital for optimizing the scientific return from current and planned facilities. Missions and facilities, including DOE projects, that will require significant amounts of new laboratory data to reach their science goals should include within their program budgets adequate funding for the necessary experimental and theoretical investigations.

Preparing for Tomorrow

Senior Reviews

Ground-based astronomical observatories are often long-lived, and their integrated operating costs frequently exceed their construction cost by a large factor. It is therefore good stewardship to manage the NSF portfolio wisely and to balance continued support of older facilities with the development and operation of newer ones. To address this challenge, NSF-Astronomy completed its first senior review exercise in 2006. The need for these reviews is ongoing.

CONCLUSION: Maintaining an appropriate balance in NSF's astronomy and astrophysics research portfolio and, by extension, balance in the health and scientific effectiveness of the NSF facilities requires a vigorous periodic senior review.

RECOMMENDATION: NSF-Astronomy should complete its next senior review before the mid-decade independent review that is recommended elsewhere in this report, so as to determine which, if any, facilities NSF-AST should cease to support in order to release funds for (1) the construction and ongoing operation of new telescopes and instruments and (2) the science analysis needed to capitalize on the results from existing and future facilities.

Ground-Based Optical Astronomy

OIR astronomy in the United States historically has benefited from significant private investment, with considerable progress made over the past decade in public-private collaboration and partnerships. The OIR future is certain to include ever more complex facilities.

CONCLUSION: Optimizing the long-term scientific return from the whole of the U.S. optical and infrared system requires a readjusting of the balance of the NSF-Astronomy program of support in three areas: (1) publicly operated national observatories—the combined National Optical Astronomy Observatories and Gemini facilities that currently dominate spending; (2) private-public partnerships—such as support for instrumentation at and upgrades of privately operated observatories; and (3) investment in future facilities.

Gemini is an international partnership that constructed and now operates two 8-meter optical-infrared telescopes, one in the Northern Hemisphere, the other in the Southern Hemisphere. The United Kingdom has recently announced an intention to leave the partnership in 2012, resulting in a need to replace the UK support. This change presents an opportunity to revisit the management of Gemini as it transitions to stable observatory operation.

RECOMMENDATION: To exploit the opportunity for an improved partnership between federal, private, and international components of the optical and infrared system, NSF should explore the feasibility of restructuring the management and operations of Gemini and acquiring an increased share of the observing time. It should consider consolidating the National Optical Astronomy Observatory and Gemini under a single operational structure, both to maximize cost-effectiveness and to be more responsive to the needs of the U.S. astronomical community.

Ground-Based Radio Astronomy

With the commissioning of ALMA and the expectation for SKA in the future, radio astronomy stands poised to continue to offer considerable promise in the exploration of our universe.

CONCLUSION: The future opportunities, worldwide, in radio, millimeter, and submillimeter astronomy are considerable, but U.S. participation in projects such as the Square Kilometer Array is possible only if there is either a significant increase in NSF-Astronomy funding or continuing closure of additional unique and highly productive facilities.

Ground-Based Solar Astronomy

U.S. solar astronomy is undergoing major changes with the commitment to construct the Advanced Technology Solar Telescope and the associated plan to close several existing facilities as well as to reorganize the National Solar Observatory. There have been great advances in space-based solar astronomy, most recently with the successful launch and deployment of the Solar Dynamics Observatory. In addition, there is a growing interest in the solar-terrestrial connection associated with climate research. These changes imply that it is time to reevaluate the management of the U.S. program.

RECOMMENDATION: NSF should work with the solar, heliospheric, stellar, planetary, and geospace communities to determine the best route to an effective and balanced ground-based solar astronomy program that maintains multidisciplinary ties. Such coordination will be essential in developing funding models for the long-term operation of major solar facilities such as the Advanced Technology Solar Telescope and Frequency-Agile Solar Radiotelescope, and in the development of next-generation instrumentation for them along with the funding of associated theory, modeling, and simulation science.

2

On the Threshold

A confluence of stunning discoveries, technological advances, and powerful ideas has made this a remarkable time in astronomy and astrophysics. The discovery of dark energy and exoplanets, the development of new digital detectors across the electromagnetic spectrum, dramatic advances in computing power, and big ideas from particle physics have us poised for major leaps in our comprehension of the universe and our place within it.

Over the next decade we will be able to trace our origins, from the quantum fluctuations that seeded galaxies in the infant universe, to the origin of atoms and dark matter, to the first stars and galaxies, and to the formation of planetary systems like ours. We are also primed to understand how the most exotic objects in the universe work, including supermassive black holes and neutron stars, as well as to figure out how planetary systems form, how common are planets in the habitable zone around stars, and how to find evidence for life elsewhere.

During the decade we will push the frontiers of basic knowledge, using the universe as a laboratory to identify the exotic dark matter and understand the even more mysterious dark energy, probe the basic properties of neutrinos and determine how they shaped the universe, and test whether or not Einstein's theory of gravity fully describes black holes. Although astronomy is the oldest science, it is constantly being reborn, and we can anticipate great surprises from all the new tools that are becoming available such as opening up time-domain astronomy and the exploration of the universe with gravitational waves.

In what follows the committee casts the compelling questions for the next decade and beyond in four thematic areas: discovery, origins, understanding the cosmic order, and frontiers of knowledge. These questions resulted from the careful surveying of the current state of research in astronomy and astrophysics done by Astro2010's five Science Frontiers Panels (SFPs), later synthesized by the committee.[1] An assessment of the readiness of the astronomy and astrophysics enterprise to answer these questions led directly to the science program described in later chapters.

DISCOVERY

New technologies, observing strategies, theories, and computations open vistas on the universe and provide opportunities for transformational comprehension, i.e., discovery.

Science frontier discovery areas:

- ***Identification and characterization of nearby habitable exoplanets,***
- ***Gravitational wave astronomy,***
- ***Time-domain astronomy,***
- ***Astrometry,*[2] *and***
- ***The epoch of reionization.***

Scientific progress often follows predictable paths. Through keen insight and diligent pursuit, questions are asked and answered, and knowledge is recorded. But many of the most revolutionary discoveries in science are made when a new way of perceiving or thinking about the universe evaporates the fog that had obscured our view and reveals an unimagined cosmic landscape all around us. The history of astronomy is replete with these revelatory moments. This capacity of the universe to astonish us was certainly evident during the past decade. Here the committee lists just a few of the most far-reaching examples.

The surprising discovery in 1998 that the expansion of the universe is accelerating rather than slowing, due to the repulsive gravity of dark energy, has changed the way we think about the evolution and destiny of the universe and has challenged our understanding of physics at the most fundamental level. In the coming decade, an optimized and coordinated set of facilities on the ground and in space will test whether the simplest hypothesis—dark energy is the quantum energy of

[1] The charge to the SFPs and their findings are summarized in Appendix A. Their reports are contained in the present report's companion volume, National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2011.

[2] Astrometry is the measurement of the motions of stars.

the vacuum—is the correct explanation or if something more exotic is needed, as must be the case for the inflationary epoch, an earlier period of acceleration. It is even possible that a modification of Einstein's general relativity will be needed. Either way, the implications for both astronomy and physics are profound.

Telescopes are time machines: because light travels across the cosmos at a finite speed, the most distant objects probe the furthest back in time. The 13.7-billion-year-old cosmic microwave background is seen in the millimeter band. The latest record holder (early 2010) for the most distant object is a gamma-ray burst that occurred 13.1 billion years ago when the universe was 0.6 billion years old. It was detected by a NASA Explorer program satellite called Swift, and its distance was measured by follow-up observations from telescopes on the ground. In the coming decade, powerful new observatories on the ground and in space will allow us to push back to still earlier times and glimpse the end of the cosmic dark ages signaled by the formation of the first-ever luminous sources in the universe—the first generation of stars.

Closer to home, the past decade has seen the discovery of well over 400 planets orbiting nearby stars. Although the existence of extrasolar planets had long been anticipated, the astonishing discovery is that the planets and their orbits seem to be nothing like our own. In the coming decade, new facilities on the ground and in space will enable us to detect potentially life-bearing planets similar to Earth.

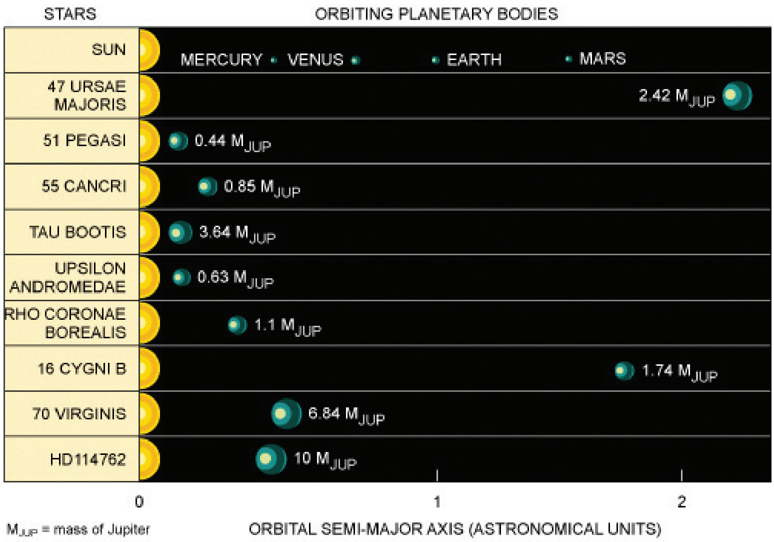
Looking forward, the most promising areas for revolutionary discoveries are highlighted in the following subsections. This is indeed a special time in history. The unexpected can be expected with confidence.

The Discovery of Habitable Planets

We are rapidly building our knowledge of nearby analogs to our own solar system's planets, most recently with the launch of NASA's Kepler mission. The salient feature of the planetary menagerie of which we are currently aware is its diversity—in every measureable sense—of the properties of the planets as well as the properties of the stars around which they orbit. We are also improving our understanding of the planet formation process, and ALMA is expected to unveil the birthing of new worlds.

Until now detection methods have only been able to discover massive planets rivaling the giants in our solar system (Figure 2.1 upper) or larger objects (Figure 2.1 lower). The most profound discovery in the coming decade may be the detection of potentially habitable Earth-like planets orbiting other stars. To find evidence that life exists beyond our Earth is a longstanding dream of humanity, and it is now coming within our reach.

The search for life around other stars is a multi-stage process. Although JWST may be able to take the first steps, more complex and specialized instrumentation



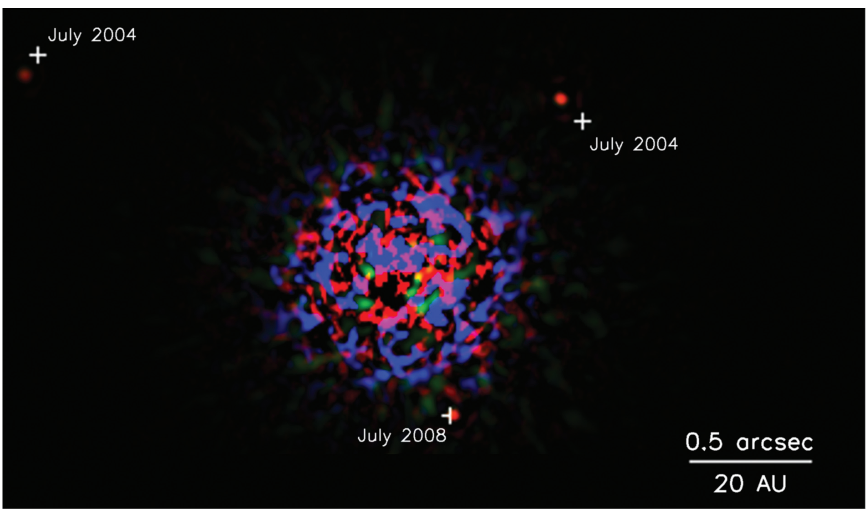


FIGURE 2.1 *Upper:* Montage of some of the first extrasolar systems discovered using the radial velocity technique, compared with our inner solar system. SOURCE: Geoff Marcy, University of California, Berkeley, and Paul Butler, Carnegie Institution for Science. *Lower:* Adaptive optics image obtained at the Gemini and Keck Observatories of three planetary-mass objects orbiting the nearby A star HR 8799. The bright light from the star has been subtracted to enable the faint objects to be seen. A dust disk lies just outside the orbits of the three planets, just as in our solar system the Kuiper belt lies outside the orbit of Neptune at 30 AU. SOURCE: National Research Council of Canada–Herzberg Institute of Astrophysics, C. Marois and Keck Observatory.

is also needed, requiring a longer-term program. First, the frequency with which Earth-size planets occur in zones around stars where liquids such as water are stable on planetary surfaces must be measured (see Box 2.1). Stars will then be targeted that are sufficiently close to Earth that the light of the companion planets can be separated from the glare of the parent star and studied in great detail; this will allow us to find signatures of molecules that indicate a potentially habitable environment. Here, the opportunities are suddenly bountiful, as we have understood over this past decade that, for example, stars much lower in mass than our Sun may have orbiting habitable planets that are much easier to spot. Thus, the plan for the coming decade is to perform the necessary target reconnaissance surveys to inform next-generation mission designs while simultaneously completing the technology development to bring the goals within reach. This decade of dedicated preparatory work is needed so that, one day, parents and children can gaze at the sky and know that a place somewhat like home exists around "THAT" star, where life might be gaining a toehold somewhere along the long and precarious evolutionary process that led, on Earth, to humankind. And perhaps it is staring back at us!

A Bold New Frontier: Gravitational Radiation

In the coming decade, a radically new window on the cosmos will open, with the potential to reveal signals of phenomena ranging from the processes that shaped the earliest era of the universe to the collisions and mergers of black holes in the more recent history of the universe. Einstein's theory of relativity tells us that space and time are inextricably linked to form space-time (Figure 2.2). Space-time is malleable: its shape is determined by the distribution of mass and energy in the universe. Massive bodies ripple space-time as they move, creating gravitational waves that propagate through the cosmos at the speed of light, unimpeded by even the densest material. The direct detection of gravitational waves requires measurements at a level of exquisite precision and sensitivity that is just now within our reach.

The daunting challenges associated with building kilometer-size detectors whose distortion by passing gravitational waves can be measured to less than one-thousandth the radius of a single proton have been overcome. By mid-decade a worldwide array of ground-based detectors such as Advanced LIGO will be operating. Like electromagnetic waves, gravitational waves span a spectrum, with more massive objects typically radiating at longer wavelengths. These ground-based experiments will probe the short-wavelength part of the spectrum, enabling us to observe the mergers of neutron stars and possibly to see the collapse of a stellar core in the fiery furnace of a supernova explosion.

However, even more promising are signals in a completely different part of the gravitational wave spectrum, at longer wavelengths, predicted to result from mergers of massive black holes during the build-up of galaxies. Detecting these

BOX 2.1
Other Worlds Around Other Stars

The detection and study of exoplanets—planets orbiting other stars—is expanding into the realm of Earth-like planets, less than 15 years after the discovery of the very first planet orbiting a star like the Sun. More than 400 planets are known, most discovered by the ground-based Doppler spectroscopic technique, in which telescopes look for a slight variation in radial velocity in stars like the Sun, and in smaller stars. An operating "transit" telescope in space today is capable of detecting planets the size of our own and smaller (Figure 2.1.1). NASA's Kepler mission, launched March 6, 2009, observes more than 100,000 stars in the "Orion arm" of our Milky Way galaxy for a telltale dip in their light output which, if regular and repeatable, represents the passage or transit of a planet in front of the star. A French and European Space Agency precursor to Kepler, called COROT, has during its 2½ years of observations already detected planets as small as about 1.7 times the diameter of Earth. With these missions in operation, we will know in the next 5 years just how common Earth-size planets located on short orbits close to their stars might be in our galactic neighborhood.

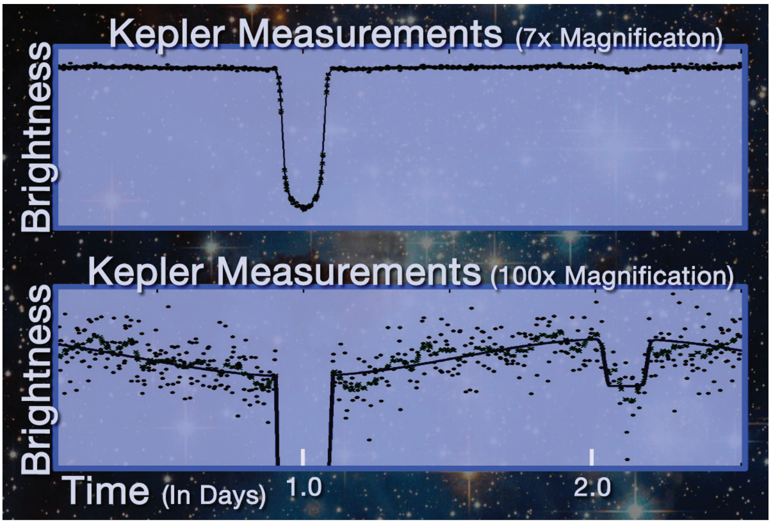


FIGURE 2.1.1 Kepler measurements of the light from HAT-P-7. The larger dip is that due to a planet about 1.4 times the radius of Jupiter transiting in front of the star, reducing the light of the star by about 0.7 percent. Such a drop has been observed from ground-based telescopes. However, the smaller drop, about 0.013 percent of the light of the star, is seen by Kepler as the planet itself passes behind the star—hence Kepler is directly detecting the light of the planet itself. Such accuracy and precision are beyond ground-based telescopes and are sufficient to detect an Earth-size planet in transit across Sun-like stars. SOURCE: NASA press release and W.J. Borucki, D. Koch, J. Jenkins, D. Sasselov, R. Gilliland, N. Batalha, D.W. Latham, D. Caldwell, G. Basri, T. Brown, J. Christensen-Dalsgaard, et al., Kepler's optical phase curve of the Exoplanet HAT-P-7b, Science 325:709, 2009.

Meanwhile, exoplanets ranging in size from Jupiter to Neptune are being studied from ground- and space-based observatories, revealing exotic weather systems and strange chemical patterns that differ from those in our solar system (Figure 2.1.2). On HD189733b, in a close circular orbit around its star, day-night temperatures are so extreme that supersonic winds may flow around the Jupiter-size planet. The Spitzer infrared space telescope has measured the light from a number of Jupiter-class exoplanets, hence determining atmospheric compositions. HD80606b, a giant planet observed by Spitzer, has an elliptical orbit that brings it alternately close to and far from its parent star so that its atmospheric temperatures change by many hundreds of degrees Celsius over 6 hours. Data on planet sizes, when combined with ground-based measurements of the planetary masses, yield densities. Many of these planets are less dense than gaseous Jupiter, whereas others are much denser, indicating a range of interior compositions and structures. Spitzer has the capability to see planets less than twice the diameter of Earth transiting the smallest stars, or M dwarfs, and its successor the James Webb Space Telescope will be even more sensitive when launched in 2015. The era of study of the properties of rocky planets around other stars, cousins of Earth, is underway.

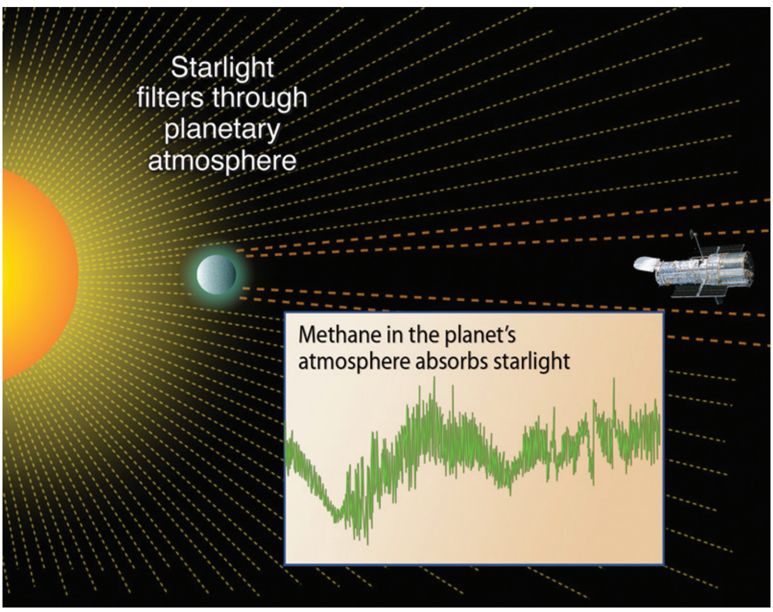


FIGURE 2.1.2 Spectrum (data points) of the exoplanet HD 189733b taken with the Hubble Space Telescope NICMOS instrument, compared with two model atmospheric compositions. The better fit with methane constitutes the first evidence for an organic molecule in an exoplanet, in this case one about the size and mass of Jupiter orbiting very close to its parent star. SOURCE: Inset adapted from M.R. Swain, G. Vasisht, and G. Tinetti, The presence of methane in the atmosphere of an extrasolar planet, Nature 452:329-331, 2008.

FIGURE 2.2 The source 3C 75, shown here in X-rays (blue) and radio waves (pink), is a rare example of two galaxies caught in the act of merging. Not only do their stars merge, but their central black holes—each producing a pair of jets containing gas moving outward at a speed close to that of light—also will do likewise in perhaps a few hundred million years. Many similar mergers involving smaller black holes in the nuclei of younger galaxies are thought to have taken place. When black holes coalesce, they create intense bursts of gravitational radiation. SOURCE: X-ray—NASA/CXC/AIfA/D. Hudson and T. Reiprich et al. Radio—NRAO/VLA/NRL.

signals will require deploying a space-based observatory with detectors separated by millions of kilometers to achieve the required sensitivity. Detection of these mergers would provide direct measurements of the masses and spins of supermassive black holes and the geometry of the universe on its largest scales. Powerful tests of our understanding of how black holes and galaxies form and evolve will be possible. We are on the verge of a new era of discovery in gravitational wave astronomy.

In addition, gravitational waves could have been created by exotic processes occurring in the young universe and would have been propagating freely to us ever since. Several speculative sources such as cosmic strings and abrupt changes in the form that the contents of the universe assumed—phase changes, like the change from water to ice—have been suggested, but the truth is that we do not quite know what to expect. A possible way to see if there are any measurable signals with wavelengths of roughly light-years employs very precise radio measurements of naturally occurring cosmic "clocks" called pulsars.[3] Spread across the sky, the separations between these cosmic clocks will change as a long-wavelength gravitational wave passes by, potentially measurably changing the arrival times of their radio pulses.

Opening the Time Domain: Making Cosmic Movies

By eye, the universe appears static apart from the twinkling of starlight caused by Earth's atmosphere. In fact, it is a place where dramatic things happen on timescales we can observe—from a tiny fraction of a second to days to centuries. Stars in all stages of life rotate, pulsate, and undergo activity cycles while many flare, accrete, lose mass, and erupt, and some die in violent explosions. Binary neutron stars and black holes merge, emitting, in addition to bursts of radiation, gravity waves. Supermassive black holes in the centers of galaxies swallow mass episodically and erupt in energetic outbursts. Some objects travel rapidly enough for us to measure their motion across the sky.

Our targeted studies of variations in the brightness and position of different objects indicate that we have only just begun to explore lively variations in the cosmos. If we study the temporal behavior of the sky in systematic ways and over wide ranges of the electromagnetic spectrum, we are sure to discover new and unexpected phenomena. In the highest-energy portion of the electromagnetic spectrum, where the universe shows its greatest variability, the value of viewing large areas of the sky repeatedly on short timescales has been amply demonstrated by the breakthrough capabilities of the Fermi Gamma-ray Space Telescope. The impact of such surveys will be broad and deep, and the committee gives just a few illustrative examples of what the future holds.

In our own solar system, new temporal surveys will discover and characterize a vast population of relic objects in the outer reaches of the solar system. These Kuiper belt objects, of which Pluto is the nearest large example, are the icy residue left over from the formation of our solar system about 4.5 billion years ago. As such, they are the fossil record of events that we can otherwise only theorize about.

[3] The 1993 Nobel Prize in physics was awarded to two American astronomers, Russell A. Hulse and Joseph H. Taylor, Jr., for their work on binary pulsars.

Moving farther away, monitoring the apparent motions of large samples of stars offers a three-dimensional view of the structure of the Milky Way that is unobtainable by other means. In this decade, precision space-based measurements with the European mission GAIA will map out the structure of the Milky Way in exquisite detail, enabling us to complete our understanding of the formation of our galactic neighborhood. Direct geometric measurements of distances to the galactic center, to major regions of star formation in the Milky Way, to nearby galaxies, and, most importantly, to galaxies at cosmological distances are possible using precision radio astronomy.

Stars can end their lives with dramatic explosions of astounding observational variety. A particular class, Type Ia supernovae, results from the sudden thermonuclear conflagration of a white dwarf (a dense object with the mass of the Sun and the radius of Earth) and produces a quantifiable amount of visible energy that can be used to map out the geometry of the universe. It remains a theoretical challenge to explain the empirical relation between peak brightness and duration that is used in these critical cosmological studies. Alternatively, supernova explosions of the Type II variety, which are due to the collapse of a single massive star that has exhausted its nuclear fuel, create many of the elements heavier than helium and sometimes produce gamma-ray bursts—intense flashes of gamma rays lasting only seconds (Figure 2.3). Again, we do not understand the mechanisms at

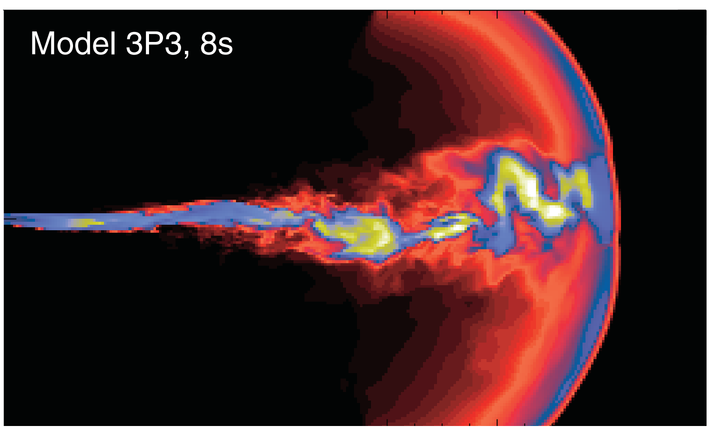


FIGURE 2.3 Numerical simulation of a gamma-ray burst showing a jet propagating out through a collapsing, massive star. Many gamma-ray bursts are associated with the supernova explosions of massive stars. The powerful bursts of gamma rays are produced by hot gas moving outward through the collapsing star at close to the speed of light. The most distant discrete source that has been observed thus far in the universe is a gamma-ray burst. SOURCE: W. Zhang, S.E. Woosley, and A. Heger, The propagation and eruption of relativistic jets from the stellar progenitors of gamma-ray bursts, Astrophysical Journal 608:365-377, 2004. Reproduced by permission of AAS.

work. The correct answers are quite likely to surprise us. Time-domain surveys of the sensitivity and scope envisioned in the coming decade will increase by orders of magnitude the number and character of stellar explosions that we can study, allowing us to connect variations in the host galaxies and progenitors to the energy and characteristics of the explosions. Supernovae are critical markers both for mapping out the cosmos and for understanding the formation of heavy elements that are found in all of us, and so these studies are essential for understanding our origins.

By surveying large areas of the sky repeatedly, once every few days, we anticipate the discovery of the wholly unanticipated. Endpoints of stellar evolution we have yet to imagine, and the behavior of ordinary stars outside our experience, could be discoveries that cause us to dramatically revise our cosmic understanding. Exotic objects and events never before anticipated may be revealed. The full realization of time-domain studies is one of the most promising discovery areas of the decade. Advanced gravitational wave detectors will open up a new window on the transient universe, including the last stages of binary neutron star and black hole mergers. Studying electromagnetic counterparts of gravity wave bursts will help illuminate the nature of the sources.

Giving Meaning to the Data: Cyber-Discovery

The powerful surveys described above will produce about a petabyte (1 million gigabytes) of data—roughly as much data as the total that astronomers have ever handled—every week. The data must be quickly sifted so that interesting phenomena can be identified rapidly for further study at other wavelengths. Interesting phenomena could also be discovered by cross-correlating surveys at different wavelengths. Vast numbers of images must be accurately calibrated and stored so that they can be easily accessed to look for motion or unusual behavior on all timescales. As daunting as it sounds, the technology and software that enable the accessing and searching of these enormous databases are improving all the time and will enable astronomers to search the sky systematically for rare and unexpected phenomena. This is a new window on the universe that is opening thanks to the computer revolution.

Another way in which computers will enable discovery in the coming decade is through increasingly sophisticated numerical simulations of the complex physical systems that are at the heart of much of astrophysics. The merging of two black holes, the growth of disks and the planets that form within them, the origin of large-scale structures that span the cosmos, and the formation of galaxies from the cosmic web are examples. Such simulations have great potential for discovery because they can illuminate the unanticipated behavior that can emerge from the interactions of matter and radiation based on the known physical laws. Through computer modeling, we understand the deep implications of our very detailed observational data and formulate new theories to stimulate further observations.

Discovery Through the Power of Mathematics, Physics, and the Imagination

Finally, it is important to remember that many of the most far-reaching and revolutionary discoveries in astronomy were not solely the direct result of observations with telescopes or numerical simulations with computers. Rather, they also sprang from the imagination of inspired theorists thinking in deep and original ways about how to understand the data, and making testable predictions about new ideas. Examples range from the prediction that the chemical elements heavier than hydrogen and helium must have been created inside nuclear furnaces in the cores of stars, to the idea that the infant universe underwent a period of extremely rapid expansion called inflation, to the prediction of exotic objects like black holes, neutron stars, and white dwarfs, and the prediction that planets are a typical byproduct of normal star formation.

In the coming decade, major challenges loom that require the development of fundamental new theories. Observations and computer simulations are necessary components, but to complete the path from discovery to understanding, theorists will need to freely exercise their imaginations.

ORIGINS

Study of the origin and evolution of astronomical objects including planets, stars, galaxies, and the universe itself can elucidate our origins.

Science frontier questions related to origins:

- ***How did the universe begin?***
- ***What were the first objects to light up the universe, and when did they do it?***
- ***How do cosmic structures form and evolve?***
- ***What are the connections between dark and luminous matter?***
- ***What is the fossil record of galaxy assembly from the first stars to the present?***
- ***How do stars form?***
- ***How do circumstellar disks evolve and form planetary systems?***

Astronomical science is the study of origins. Where did we come from as an intelligent species on a single planet in a vast cosmos? How did the cosmos itself begin, and how did the first stars and the structures of star clusters, galaxies,

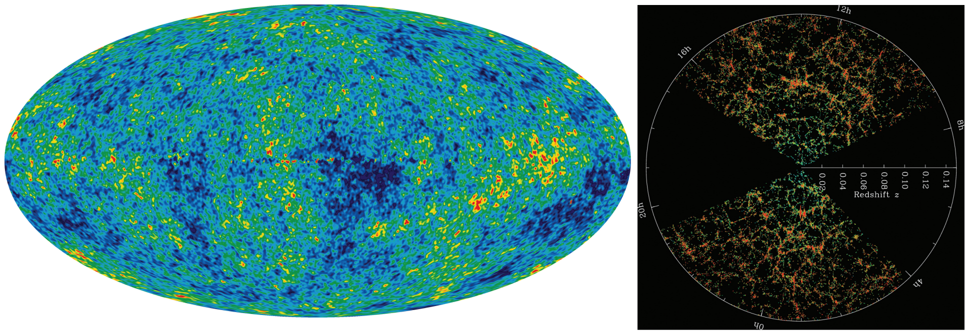


FIGURE 2.4 *Left:* Image of the tiny fluctuations in temperature—roughly 10 parts per million—of the cosmic microwave background as observed by the WMAP satellite. The radiation that is observed was emitted when the universe was roughly 400,000 years old. The red regions are warmer and the blue regions colder. A careful analysis of these data shows that there is a preferred angular scale of 1 degree—about the size of the Moon—called the first acoustic peak in the dark matter density containing roughly 100,000 galaxies like our Milky Way galaxy. SOURCE: NASA/Wilkinson Microwave Anisotropy Probe Science Team. *Right:* The same feature can be seen in the distribution of galaxies around us today as exhibited by the Sloan Digital Sky Survey in a 2.5-degree-thick slice of the northern equatorial sky where color corresponds to galaxy luminosity. Here it is called a baryon acoustic oscillation. The expansion of the universe by a factor of 1,000 makes the size of the feature about 400 million light-years. Monitoring the growth of this feature as the universe expands is one of the best approaches to understanding the behavior of dark energy. SOURCE: Michael Blanton and Sloan Digital Sky Survey (SDSS) Collaboration, http://www.sdss.org.

and clusters of galaxies arise? Is our universe just one of an infinite number of others—one with properties allowing for life—or is it instead an extraordinarily remarkable and singular thing? How did *our* galaxy, Sun, and planet Earth form? These questions, expressed in different ways, have profoundly affected human beings across cultures for as long as human thought has been written down or propagated through oral tradition. The remarkable findings of the 20th century were that the universe had a single explosive origin and that the galaxies, stars, and planets we observe not only are common, but also are the evolved expression of structure embedded within the universe since its very beginning (Figure 2.4). These realizations have both scientific and philosophical implications, and they have spawned a multitude of fascinating questions about our origins that we are racing toward answering in the 21st century.

The Origin of the Universe: The Earliest Moments

We know, from observations over the last decade of the microwave background and the early constituents of the universe, that the universe—all matter, space, and time itself—began 13.7 billion years ago in the big bang, and we are now telling the story of the universe with a confidence that has grown considerably over the last 10 years. We think that, just after the big bang, the universe was totally different from what it is today—none of the elementary particles that we know compose the matter of today were present. The universe was an incredibly dense knot of highly curved space-time. Then came an era of cosmic inflation, during which the universe rapidly expanded by a truly enormous factor (at least a factor of 100 trillion trillion in growth). The laws of quantum mechanics suggest that random fluctuations at the time of inflation would have produced microscopic density variations from place to place, which expanded with the universe to became macroscopic variations today. Remarkably, astrophysicists are able to connect the giant filaments and voids in the great cosmic web of galaxies to the seeds from which they grew. However, just as the cause of the current acceleration is unknown, so also is the underlying detailed physics of inflation still a complete mystery.

About 400,000 years after the big bang, the continued expansion and cooling of the universe had dropped the temperature to about 3,000 degrees, which was cool enough for the first hydrogen atoms to form. This is the epoch of recombination. A fundamental change in the universe occurred at that time when the cosmos went from being filled with a plasma that was opaque to light to being filled with an atomic gas through which light could freely pass. It is this freely streaming radiation that we observe at radio wavelengths as the faint glow known as the cosmic microwave background (CMB). The near uniformity of the CMB observed across the sky and the nature of the minute brightness fluctuations we measure in the CMB are just what is expected if inflation occurred. The CMB is therefore a fantastic signal telling us about the early universe.[4]

The First Sources of Light and the End of the Cosmic Dark Ages

Following the recombination and the formation of the first atoms, the early universe was a nearly formless primordial soup of dark matter and gas: there were no galaxies, stars, or planets. The background radiation had a temperature that quickly cooled to a temperature below that of the coolest stars and brown dwarfs known today. This was truly the dark ages. However, things began to change when the slightly denser regions left over from inflation began to contract under the relentless pull of gravity. It took a few hundred million years, but eventually these dense regions gave birth to a variety of objects—the first stars, and black holes that glowed through accretion of matter—so that the universe became filled with light (Figure 2.5).

[4] The 1978 and 2006 Nobel Prizes in physics were awarded to Americans, Arno A. Penzias, Robert W. Wilson, John C. Mather, and George F. Smoot, for CMB research.

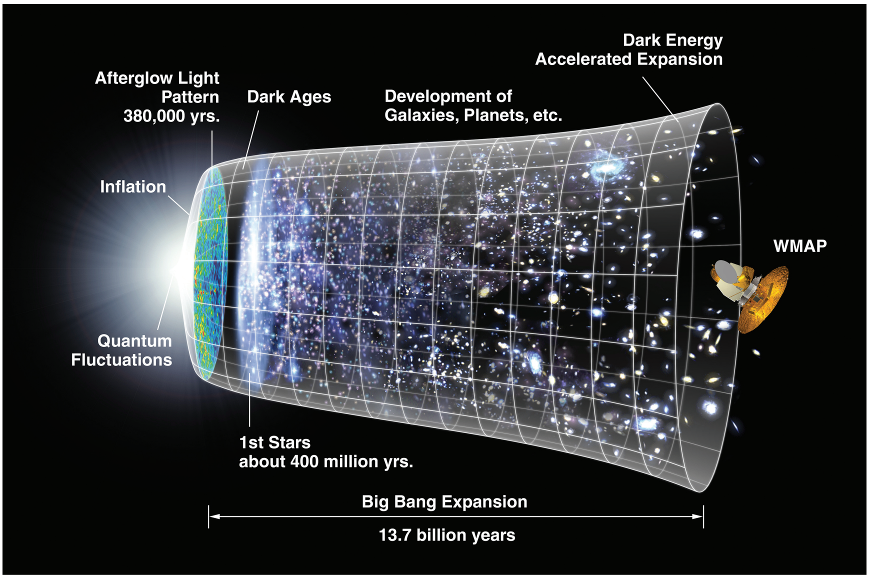


FIGURE 2.5 The cosmic timeline, from inflation to the first stars and galaxies to the current universe. The change in the vertical width represents the change in the rate of the expansion of the universe, from exponential expansion during the epoch of inflation followed by a long period of slowing expansion during which the galaxies and large-scale structures formed through the force of gravity, to a recent acceleration of the expansion over the last roughly billion years due to the mysterious dark energy. SOURCE: NASA Wilkinson Microwave Anisotropy Probe Science Team.

This event signaled the end of the dark ages and the dawn of the universe as we know it today. This first generation of stars—made purely from the big bang's residue of hydrogen and helium—may have been unusually massive and hot compared to today's stars like the Sun. Their intense ultraviolet light traveled out into the surrounding universe and struck the atoms there, breaking many of them apart into nuclei and electrons. This key moment in cosmic history is therefore called the epoch of reionization. The characterization of this transition and its spatial structure is being attempted by ground-based radio antennas.

These events lie largely in the realm of theory today, and existing telescopes can barely probe this mysterious era. Over the next decade, we expect this to change. A new window on the cosmos is being opened in several wavelengths: radio astronomers are constructing telescopes that will tell us when and where the first stars in the universe formed by mapping their effect on the primordial hydrogen at the end of the dark ages, and are planning those that will be able to directly observe the primordial hydrogen atoms that permeated the dark ages of the universe (Figure 2.6). Large X-ray telescopes can detect the first massive black

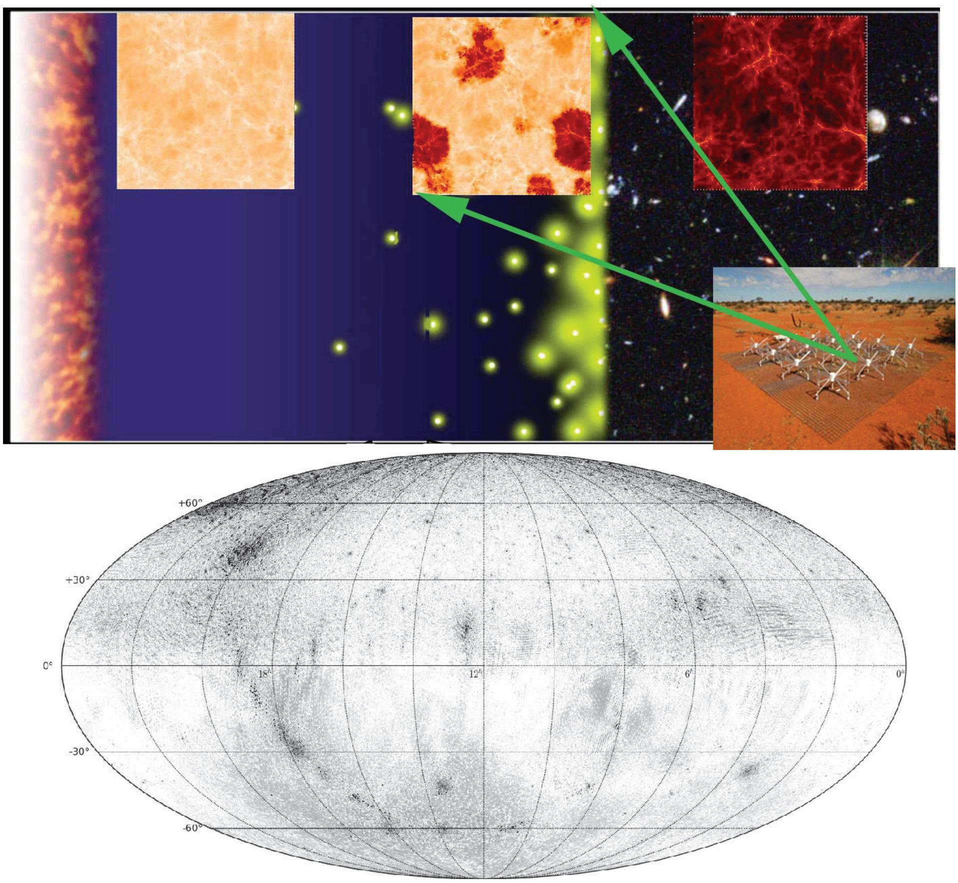


FIGURE 2.6 *Top:* Schematic of the evolution from left to right of an inflationary universe to recombination to reionization and first star/galaxy formation to today's Earth-bound telescopes. Overlaid in tiles are predicted 21-cm signals from the Murchison Widefield Array. SOURCE: S. Furlanetto, University of California, Los Angeles; J. Lazio, JPL; and C. Lonsdale, MIT-Haystack. *Bottom:* The same signals detected at 150 MHz in an all-sky map from the Precision Array to Probe the Epoch of Reionization. SOURCE: A.R. Parsons, D.C. Backer, R.F. Bradley, J.E. Aguirre, E.E. Benoit, C.L. Carilli, G.S. Foster, N.E. Gugliucci, D. Herne, D.C. Jacobs, M.J. Lynch, et al., The precision array for probing the epoch of re-ionization: Eight station results, Astronomical Journal 139(4):1468-1480, 2010.

holes and quasars at very great distances. Although the "first stars" are most likely too faint to observe individually, they should form in the collapsing clumps of gas that are the small building blocks of future galaxies like our Milky Way. ALMA and the EVLA will detect and conduct studies of many of these protogalaxies. JWST should be able to image them as well, while the proposed next generation of giant ground-based optical-infrared telescopes would investigate these first objects in detail (measure their mass, chemical composition, and ages). There is also growing evidence that many gamma-ray bursts are the explosive deaths of very massive stars and sometimes resulting in the formation of the first generation of black holes with the unusual chemical compositions expected for the first stars (nearly devoid of elements heavier than hydrogen and helium). The study of the coolant deaths of these stars offers another way to learn about the first stars.

The Origin of Galaxies and Large-Scale Structure

The small protogalactic fragments containing the first stars were embedded in halos of dark matter, which formed first and provided most of the total mass. Through their mutual gravitational attraction, these small fragments of gas and dark matter would have fallen slowly toward other such objects, collided, and then merged into larger objects. This process continued over the entire history of the universe: in the densest regions, small objects merged to form medium-size objects that later merged to form large objects (Figure 2.7). Over time even larger

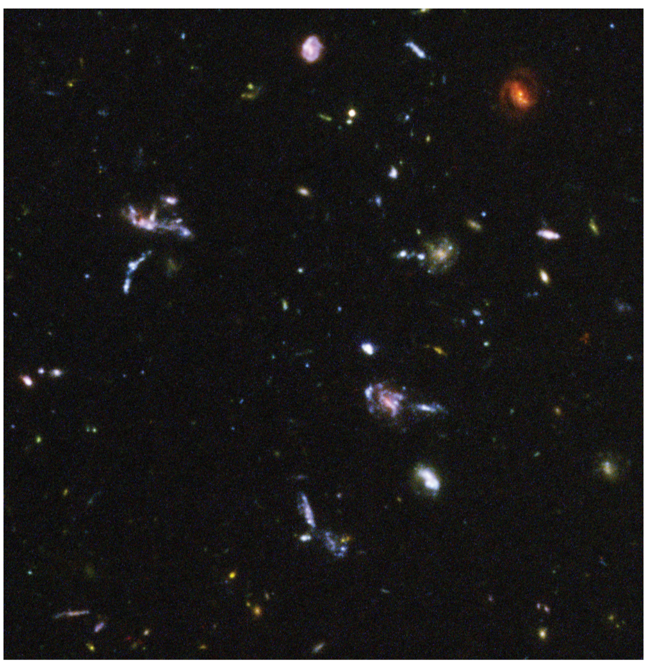


FIGURE 2.7 This enlargement of part of the Hubble Ultra Deep Field shows distant young galaxies in the process of forming; several galaxy mergers and unusual structures are evident. SOURCE: NASA, ESA, S. Beckwith, and the Hubble Ultra Deep Field team.

structures formed: groups and clusters of galaxies, and the filaments that connect these clusters to one another in the vast cosmic web.

Thanks to major surveys of the last decade, we now have a precision map of the cosmic cartography of the present-day local universe that is the result of this process of merging. Over the next decade it will be a high priority to extend such precision mapping over cosmic time: to have, in effect, a 13-billion-year-long movie that traces the buildup of structure since the universe first became transparent to light. This can be done by using radio telescopes to provide more detailed maps of the cosmic microwave background and to detect the atomic hydrogen gas all the way back into the dark ages; large spectroscopic surveys in the visible and near-infrared to trace the distribution of galaxies; gravitational lensing to trace the distribution of the dark matter halos; ultraviolet spectroscopic surveys to map out the warm tenuous gas lying in the vast cosmic filaments; and radio Sunyaev-Zel'dovich effect and X-ray surveys that reveal the distribution of the hot gas found in groups and clusters of galaxies.

Most stars with masses smaller than that of the Sun will live even longer than the current age of the universe. This means that low-mass stars that formed at any time over the history of the universe are still present in galaxies today. Thus, detailed studies of the populations of stars within a galaxy provide a fossil record that traces the history of star formation over the whole course of the galaxy's evolution. Such studies also trace the buildup of the heavy elements in the galaxy as successive generations of stars formed, converted their light elements into heavier ones, and then exploded, contributing their newly formed heavier elements to their surroundings. This observational approach is currently practical only in the Milky Way and its nearest neighbors. Future generations of optical telescopes in space and large ground-based telescopes will enable us to extend this technique farther afield and study the histories of the full range of galaxies by imaging their stellar populations.

The Origin of Black Holes

In the past decade we have discovered two remarkable things about black holes. The first is that supermassive black holes—objects with masses of a million to billions of times the mass of the Sun—are found in the centers of all galaxies at least as massive as our Milky Way. This means that the formation of black holes is strongly related to the formation of galaxies. The second is that supermassive black holes were already present, and growing rapidly, at a time less than a billion years after the big bang, when the first galaxies were being assembled. This strains our understanding of the early universe: How could such dense and massive objects have formed so rapidly? Which formed first, the black hole or the galaxy around it? Radio observations of star-forming molecular gas in some of the most distant galaxies suggest that a black hole is present before the formation of a massive galactic halo. ALMA and the EVLA may provide more such examples.

But we cannot answer these questions definitively yet, because we do not have a robust theory for how supermassive black holes form. In the coming decade we expect a major breakthrough in our understanding. A space-based observatory to detect gravitational radiation will allow us to measure the rate at which mergers between less-massive black holes contributed to the formation process. Are the supermassive black holes we can now detect only the tip of the iceberg (the biggest members of a vast unseen population)? Deep imaging surveys in the near-infrared and X-ray, with follow-up spectroscopy with JWST and ground-based extremely large telescopes, will detect and study the growth of the less massive objects through the capture of gas and accompanying emission of electromagnetic radiation. These surveys will also allow us to search for such black holes at even earlier eras: back to the end of the dark ages.

The Origin of Stars and Planets

Looking up on a clear night from a dark location, we see that the sky is full of stars. Telescopic observations by Galileo revealed that the Milky Way's white band traversing high across the summer and fall sky can be resolved into countless stars. Gazing upon the winter constellation of Orion, the sharp eye will note the fuzzy Orion Nebula (see in Box 2.4 Figure 2.4.3) with its nursery of stars born "yesterday" in cosmic time—not long after the first humans walked. Nearby is the famed Pleiades star cluster—formed when dinosaurs still roamed Earth. In contrast, some stars of our galaxy are nearly as old as the universe itself. The story of how successive generations of stars form out of the gas and dust in the interstellar medium in both benign and exotic environments is fundamental to our understanding of, on the larger scale, the galaxies in which stars reside and, on the smaller scale, the planetary systems they might host.

What was it about the Sun's birth environment or its star formation process that determined the final properties of our solar system versus that of other planetary systems? (See Box 2.2.) How and on what timescale did the solar mass build up, and how much gas and dust were left over for planet formation? How rapidly did the high-energy radiation of young stars disperse their gas disks, ending the phase of major planet formation? Do all environments yield the same mass distribution of stars, and what determines the lower and upper mass limits in the distribution (Figure 2.8)? What is the star formation history of our galaxy in particular, and of galaxies in general? Does star formation regulate itself, or are there external factors at work?

A key aim of studies in the next decade is to understand, through both observations and theory, the process of star formation over cosmic time. Beginning near

BOX 2.2
The Origin of Planets

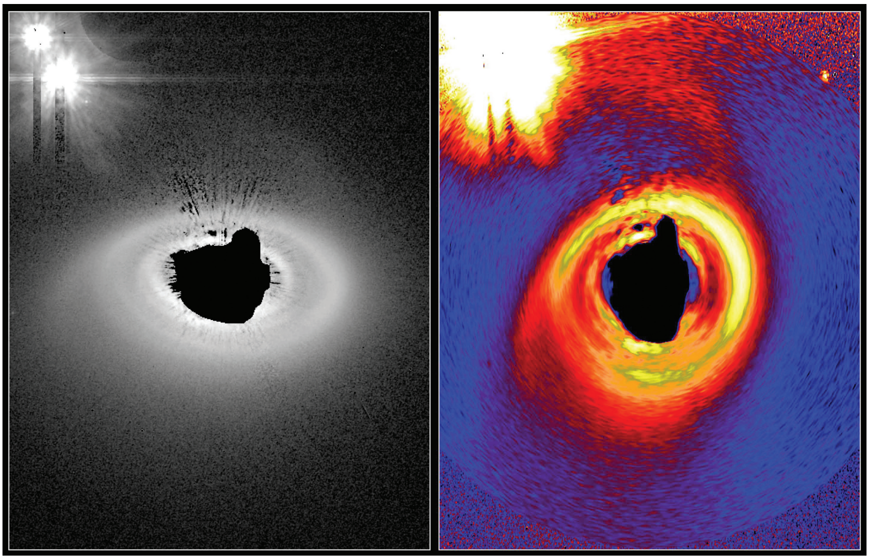
After literally centuries of speculation as to how our own planetary system formed, the past two decades of ground- and space-based astronomy have resolved the general question of planetary origin: planets form in the disks of gas, dust, and ice that commonly surround newly born stars (Figure 2.2.1).

That such disks are seen around more than 80 percent of the youngest stars in nearby stellar nurseries strongly implies that planets are a frequent outcome of star formation. But the details of how planets form within disks are still being revealed by current astronomical techniques including imaging from Hubble, Spitzer, and the largest ground-based telescopes, plus theoretical studies including computer modeling. Disks start out being dominated by gas—the hydrogen and helium of the primordial cosmos salted with the heavy elements out of which planets and life are composed—and evolve with time into thinner dust-only structures. Although most if not all stars like our Sun may possess disks early in their histories, how many of these turn into planetary systems is not known.

Over the past decade facilities such as NASA's Spitzer Space Telescope and the federally supported CARMA, SMA, and VLA telescopes, and various space- and ground-based coronographic instruments, have advanced our understanding of disk properties and evolution considerably. The next decade of astronomical facilities should have the capability to see the effects of young planets embedded within the disks from whence they arose.

Is the typical outcome of planet formation gas-giant worlds with panoplies of satellites, like Jupiter and Saturn, or rocky worlds like Earth with atmospheres and surface liquids stabilized by being suitably near to stable parent stars like the Sun, or some completely different kind of object that is not represented in our solar system? The answer to this question will require a complete census of planetary systems in the nearby portion of our galaxy. By compiling the statistics of planetary sizes, masses, and orbits for a range of planetary systems around stars of different masses, compositions, and ages, it will be possible to gain deep insight into the processes by which worlds such as our own come into being.

FIGURE 2.2.1 Images of dust disks around young stars. *Top:* Image taken with the Hubble Space Telescope of disk around the young, 5-million-year-old star HD141569. SOURCE: NASA, M. Clampin (STScI), H. Ford (JHU), G. Illingworth (UCO/Lick), J. Krist (STScI), D. Ardila (JHU), D. Golimowski (JHU), the ACS Science Team, and ESA. *Bottom:* Edge-on view of disk around AU Mic, a nearby 10- to 20-million-year-old star. SOURCE: M.P. Fitzgerald, P.G. Kalas, G. Duchêne, C. Pinte, and J.R. Graham, The Au microscopic debris disk: Multiwavelength imaging and modeling, Astrophysical Journal 670:536, 2007. Reproduced by permission of AAS.



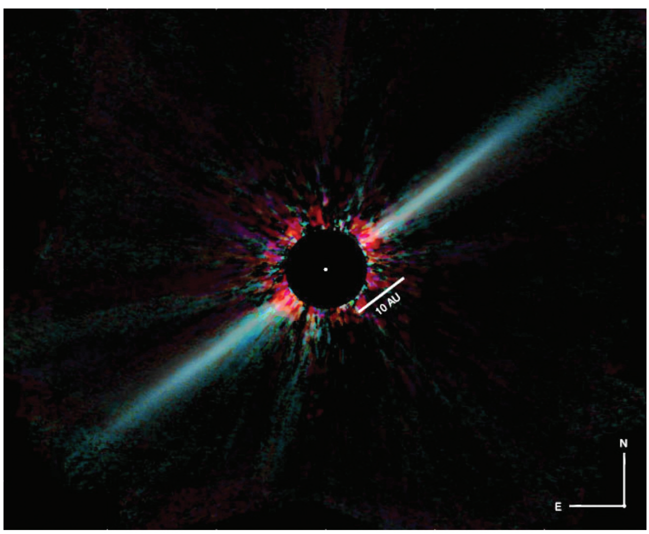

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FIGURE 2.8 This Hubble image shows a young (5 million years old) cluster of massive stars eroding the dusty material around them in a region in our neighboring galaxy, the Small Magellanic Cloud. SOURCE: NASA, ESA, and the Hubble Heritage team (STScI/AURA).

home, detailed spectroscopic measurements at short radio wavelengths will track the internal dynamics of the dust-enshrouded molecular clouds that fragment and seed the star-forming cores within a few hundred light-years of our Sun (see Figure 2.2.1 in Box 2.2). Given the importance of high-mass stars to the production and dispersal of heavy elements, understanding their proportion in both the benign and the more extreme star-forming environments is critical to tracking the heavy-element history of the universe.

UNDERSTANDING THE COSMIC ORDER

The combination of basic physical processes can often lead to surprisingly complex results and produce much of the intriguing cosmic order.

Science frontier questions related to understanding the cosmic order:

- ***How do baryons cycle in and out of galaxies, and what do they do while they are there?***
- ***What are the flows of matter and energy in the circumgalactic medium?***
- ***What controls the mass-energy-chemical cycles within galaxies?***
- ***How do black holes grow, radiate, and influence their surroundings?***
- ***How do rotation and magnetic fields affect stars?***
- ***How do the lives of massive stars end?***
- ***What are the progenitors of Type Ia supernovae and how do they explode?***
- ***How diverse are planetary systems?***
- ***Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?***

One of the biggest challenges in the next decade is to understand how the basic building blocks of matter and energy, governed by known physical laws, are responsible for the dazzling array of astronomical phenomena that intrigue and inspire us. Meeting this challenge will require a synthesis of a broad range of evidence and insights drawn from traditionally disparate scientific disciplines.

None of the baryonic components of the cosmos (gas, galaxies, stars, planets, life) exist in isolation. Galaxies grow by cannibalizing smaller neighboring galaxies and by capturing primordial gas clouds flowing in from the vast spaces beyond. This gas, once inside a galaxy, is the raw material for forming new stars. The big bang produced only the simplest and lightest chemical elements, hydrogen and helium. Heavier elements like oxygen and iron have been forged within the nuclear furnaces of stars and violently expelled in supernova explosions, thereby seeding the environment with the material necessary to form planets and support life.

Our goal is to use all the applicable scientific laws to understand the properties and behavior of the cosmos—in short, to find order in complexity.

Galaxies and Black Holes

The observable universe contains more than 100 billion galaxies, including our own Milky Way. Although we commonly think of galaxies as being made of stars and clouds of gas and dust, in fact more than 90 percent of the mass of galaxies is dark matter, whose nature we do not understand. And at the center of most or all galaxies lies a supermassive black hole. Thus something as common as a galaxy is both exotic and mysterious. The stars in spiral galaxies like ours are arrayed in two main components: a nearly spherical and slowly rotating "bulge" and a thin and rapidly rotating "disk" (which also contains the gas clouds that can be used to form new stars). Galaxies exhibit a bewildering array of shapes and sizes that are determined largely by the mass of the halo of dark matter surrounding them. Besides spirals, there are ellipticals, three-dimensional balls that formed most of their stars early on, and so have no gas/star disks and little star formation today; and irregulars, tiny galaxies with an abundance of gas and plenty of star formation today.

The lives of galaxies are determined by both nature and nurture, that is, by processes internal to the galaxies as well as through the influence of the surrounding environment. The most massive galaxies today would have begun forming in the early universe in the regions of the highest density of dark matter and gas. They later merged with other galaxies of comparable mass (major mergers), scrambling the disks of the merging galaxies into a single nearly spherical bulge component. The collision would also send material raining into the center of the bulge where it could be used to form and grow a supermassive black hole. In contrast, the life story of low-mass galaxies is more sedate. Originating in regions of lower density, they were only slowly supplied with gas, formed their stars gradually over the history of the universe, suffered fewer major mergers, and retained their disk-like form to the present day. These different life stories explain the strong dichotomy in the observed properties of the high- and low-mass galaxies.

Internal processes in galaxies are complex and affect their ability to make new stars. Supernovae from the explosive deaths of short-lived massive stars violently heat the surrounding gas (see Box 2.3). If the rate of such supernova explosions is high enough, they can act together to expel much of the galaxy's gas supply (see in Box 2.4 Figure 2.4.4). This will have a more severe impact on low-mass galaxies: their gravity is so weak that material can be easily ejected from them. This may explain why dark matter halos with low mass contain so few stars and so little gas today. The role played by the supermassive black hole is instead important for the lives of the most massive galaxies (which contain the most massive black holes). The energy released by the black hole during periods of intense eruptions can prevent new gas from being captured by the galaxy, explaining why the most massive galaxies are no longer forming stars.

Understanding the details of galaxies and their interstellar gas, dust, and stars requires a community of astronomers to study stellar populations, the dynamics of galaxies and clusters, interstellar and intergalactic gas, stars with a range of properties such as high and low metallicities, and stellar streams resulting from tidal interactions of galaxies, as well as studies of the wide range of galaxies around us, from the smallest dwarf galaxies to the largest spirals and ellipticals. From the analysis of stellar populations, we can study how the Milky Way assembled.

While we have a rather good description of the properties of galaxies in the present-day universe, we have far less information about how these properties have changed over the 13.7-billion-year history of the universe. The galaxies we can observe in detail teach us of the complex interplay among the components of normal and dark matter, constrained by the physical laws of the cosmos. A high priority in the coming decade will be to undertake large and detailed surveys of galaxies as they evolve across the wide interval of cosmic time—to have a movie of the lives of galaxies rather than a snapshot. See Box 2.4.

As described above, the lives of galaxies and the supermassive black holes at their centers seem to be inextricably linked. Two of the major goals of the coming decade are to understand the cosmic evolution of black hole ecosystems—the intense interplay between the black holes and their environments—and to figure out how these extremely powerful "engines" function. Black hole masses will be measured by JWST and ground-based optical and radio telescopes. Observations of black holes in the X-ray and gamma-ray regimes offer uniquely powerful insights. For example, the Fermi Gamma-ray Space Telescope as well as the ground-based atmospheric Čerenkov telescopes such as VERITAS are constantly reporting new and powerful variations of emission, in both the energy and the time domains, from large numbers of these systems over the whole sky and from cosmological distances. The Chandra and XMM-Newton X-ray observatories are being used to measure the environmental impact of energy injection from the black hole and also to give us a glimpse of matter as it swirls inexorably inward toward the event horizon at the very edge of the black hole. Future more powerful X-ray observatories will provide detailed maps of these processes, so that we can directly witness the accretion of matter (by which black holes grow) and can also understand the impact they have on the lives of their "host" galaxy.

Stars

Stars are the most observable form of normal matter in the cosmos. They have produced about 90 percent of all the radiant energy emitted since the big bang (with black holes accounting for most of the balance). Through the nuclear reactions that power them, they have taken the primordial hydrogen and helium produced during the big bang, converted this into heavier elements like carbon, oxygen, and iron, and then dispersed this material so that it can be incorporated in subsequent generations of stars and of the planets that accompany them (see in Box 2.4 Figure 2.4.3). Such recycling is proceeding continuously within galaxies like our own.

We now have a mature theory for the structure and evolution of stars. This theory is based on a synthesis of known physical processes (nuclear reactions; the

BOX 2.3
Understanding Supernova Explosions

About once every few hundred years in a galaxy like ours, a white dwarf in a binary star system explodes in a sudden thermonuclear flash as material is transferred from the companion star. The billion-degree ashes of the now incinerated white dwarf expand away from the explosion at speeds in excess of 10,000 km/s, providing a light show that can be seen halfway across the universe. It was the observation of such events, supernovae of Type Ia, that yielded the dramatic evidence of the acceleration of the universe. We still do not know what combination of stellar properties causes these rare, unstable thermonuclear ignitions, nor do we fully understand how the burning propagates throughout the star. Observational progress in this decade will come from a large increase in the number of well-observed nearby supernovae, while theoretical progress will come in two modes: an enhancement of computational power needed to understand the flame propagation and the radiative transfer processes, and a growing theoretical understanding of the ignition process and its dependence on the age and material composition of the white dwarf.

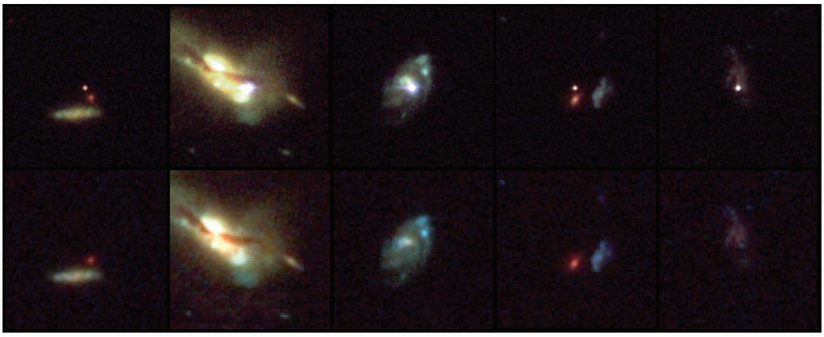


FIGURE 2.3.1 Host galaxies of distant supernovae, visible as bright point sources in the top row of images. SOURCE: NASA, ESA, and Adam Riess (STScI).

outward flow of matter, radiation, and energy). We now know that the overall life story of a star depends primarily on its mass and, secondarily, on its chemical composition. The mass of a star has a pronounced effect on the rate at which it consumes its nuclear fuel: the more mass the star contains, the shorter its life will be (it lives fast and dies young), and the more violent and spectacular its death, with explosive heating of the surrounding gas and production of a legacy corpse in the form of a neutron star or black hole.

Yet challenges remain. We know that as stars like the Sun age they lose mass in the form of a relatively steady wind, or more episodically during violent pulsa-

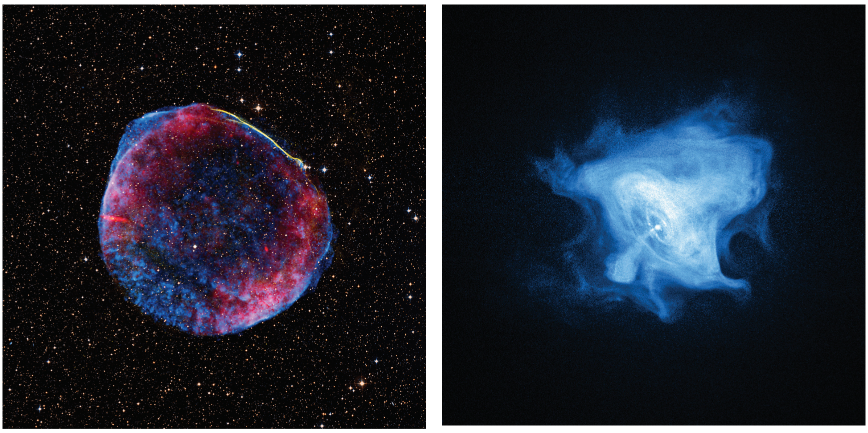


FIGURE 2.3.2 *Left:* Composite image incorporating X-ray (blue), optical (yellow), and radio (red) observations of the expanding debris from a Type Ia (accreting, then exploding, white dwarf star) supernova that was observed by humans in the year 1006. The outer rim of this supernova "remnant" traces a shock wave where cosmic-ray electrons and protons are accelerated and the magnetic field is amplified. SOURCE: NASA/CXC/Rutgers/J. Warren and J.P. Hughes et al. *Right:* The explosive death of a massive star involves the collapse of the star under its own weight followed by a violent explosion. A famous example of the aftermath of this type of supernova is the Crab Nebula, shown here in an image made by the Chandra X-ray Observatory. At the center of the image is the Crab pulsar, a neutron star that spins on its axis 30 times a second and creates two jets of relativistic particles. In death, the star seeds the surrounding gas with the chemical elements it forged during its lifespan in its nuclear furnace. These elements (like oxygen, iron, and silicon) are the raw material out of which future stars form planets like Earth. SOURCE: NASA/CXC/SAO/F. Seward et al.

tions and explosive eruptions in the late stages of the star's life. Indeed, the final end stage of a star's life depends quite sensitively on the amount of mass it retains following its evolution beyond the hydrogen-burning stage. It will also depend strongly on how rapidly the star is rotating and on the strength and nature of the magnetic fields that it has built.

This has far-reaching implications because the end states of massive stars (supernovae) determine the chemical composition of a galaxy and hence the properties of the subsequent generations of stars and planets. To understand the lives of stars and the role they play in cosmic evolution we must understand the roles of

BOX 2.4
Life Cycles in Galaxies

One of the greatest astronomical discoveries of the last century was that our own Milky Way is but 1 of 100 billion galaxies sprinkled throughout an almost inconceivably vast extent of the observable universe. Each galaxy like the Milky Way consists of billions of stars, myriad clouds of gas, and—lurking in the very center—a supermassive black hole. These components are surrounded by a large halo of dark matter particles that provide the gravitational "glue" to bind the galaxy together, but which are otherwise invisible.

When first discovered, galaxies were called "island universes" and were thought to reside in majestic isolation. Today we know that galaxies are part of a complex network of interactions with the cosmos that has governed their lives over billions of years. Most gas clouds inside a galaxy eventually collapse to form new stars, but some clouds near the galaxy center are instead captured and eaten by the massive black hole. The life-sustaining nuclear reactions inside stars create new chemical elements like oxygen, carbon, and iron. As they die, stars expel these chemical elements back to the galaxy, providing the raw material to form new stars, planets, and even life. As the gas inside a galaxy is used up in this way, it is replenished by gas flowing in through the halo of the galaxy from a primordial repository of gas in the vast spaces between the galaxies themselves.

However, this flow of gas is not one-way. When massive stars die, they explode violently and heat the surrounding gas to temperatures of millions of degrees. Some galaxies go through episodes in which the rate of such explosions is so high that the galaxy's gas supply may be blasted completely away. Intermittent powerful eruptions of the massive black hole may do the same. It is these cycles of matter and energy in and out of galaxies that determine how they were born and how they have grown. Understanding stars, black holes, and gas inside and out is a central goal in astrophysics for the next decade.

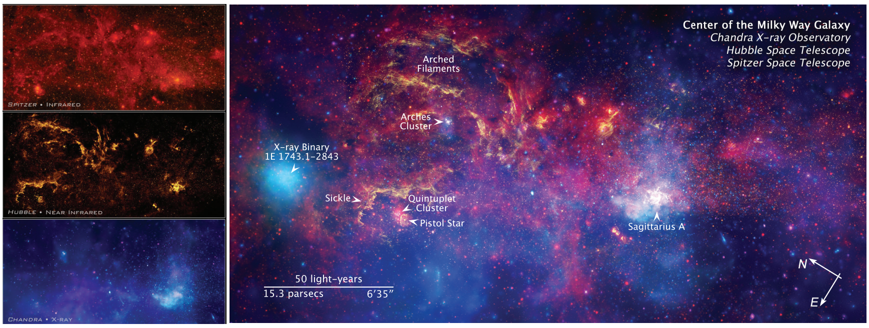


FIGURE 2.4.1 *Left:* The center of the Milky Way galaxy observed at X-ray wavelengths using the Chandra X-ray Observatory, at optical wavelengths using the Hubble Space Telescope, and at infrared wavelengths using the Spitzer Space Telescope. The 4-million-solar-mass black hole in the galactic nucleus is located in the bright region to the lower right. *Right:* Composite with the three images on the left, and annotated. SOURCE: NASA, ESA, Spitzer Science Center, Chandra X-ray Center, and Space Telescope Science Institute.

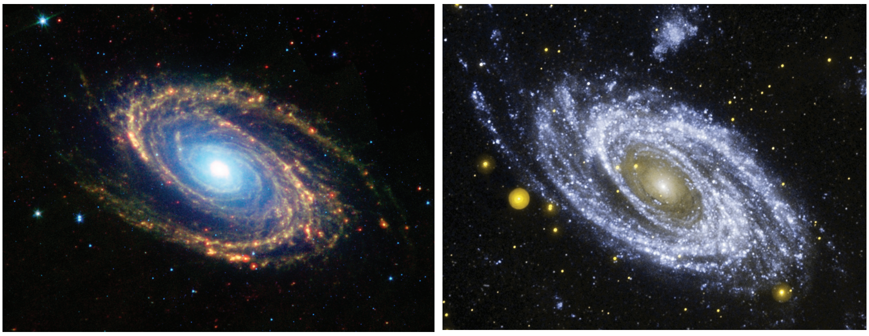


FIGURE 2.4.2 The nearby spiral galaxy Messier 81 imaged with the Spitzer Space Telescope in the infrared (*left*) and the Galaxy Evolution Explorer (GALEX) in the ultraviolet (*right*). This galaxy is very similar to our Milky Way. New stars are forming out of gas clouds concentrated in the spiral arms. A dormant supermassive black hole lurks in the bright central region. SOURCE: *Left*—NASA/JPL-Caltech/K. Gordon (University of Arizona), S. Willner (Harvard-Smithsonian Center for Astrophysics), and N.A. Sharp (NOAO/AURA/NSF). *Right*—NASA/JPL-Caltech/J. Huchra (CfA).

FIGURE 2.4.3 Hubble Space Telescope image of the Orion Nebula. This is a nearby region in the Milky Way galaxy where new stars are forming out of a surrounding gas cloud. Intense radiation from these young stars is causing the natal gas clouds to glow in a swirl of vibrant colors. SOURCE: NASA, ESA, M. Robberto (STScI/ESA), and the Hubble Space Telescope Orion Treasury Project Team.

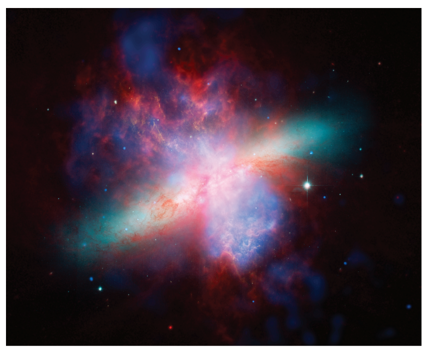


FIGURE 2.4.4 An image of the nearby galaxy Messier 82 produced using the Hubble Space Telescope, the Chandra X-ray Observatory, and the Spitzer Space Telescope. The galaxy (as seen in green) has such a large number of supernova explosions that they are blasting out much of the galaxy's gas supply (as seen in red and blue). Such events play a critical role in the life cycles of galaxies. SOURCE: X-ray—NASA/CXC/JHU/D. Strickland; Optical—NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR—NASA/JPL-Caltech/University of Arizona/C. Engelbracht.

mass loss, rotation, and magnetic fields in stellar evolution. Prospects are bright for the coming decade. All three phenomena can be assessed through high-dispersion spectroscopy. Rotational studies are possible with detailed long-term photometric monitoring. It is now becoming possible to study the structure and strength of magnetic fields on the surfaces of nearby stars, and changes in the magnetic fields can be diagnosed with X rays. At the same time, the major advance provided by the Advanced Technology Solar Telescope (ATST) will be an improved ability to observe and understand the rich array of magnetic activity exhibited by our nearest star, the Sun. Solar radio emission will be observed at high time and wavelength resolution on a continuous basis, providing unique data to combine with that of ATST.

Indeed, following the successful launch and commissioning of the Solar Dynamics Observatory (SDO; Figure 2.9), we are poised to understand the origin of the 11-year solar cycle, which underlies "space climate," by relating the surface behavior of the Sun to its interior properties, in particular at the tachocline located at 70 percent of the solar radius where the hot gas begins to undergo convective motion. In addition, the high-resolution, all-disk imaging combined with the ability to map the surface magnetic field in three dimensions as it erupts into the solar chromosphere and corona is providing unprecedented understanding of how magnetic fields behave above the solar surface both in the "quiet" Sun and during massive flares associated with active regions. This understanding is of major importance for astrophysics beyond the solar system because the Sun is the best large-scale magnetic field laboratory we have. Meanwhile, ATST will come on line in 2017 and will provide complementary diagnostics for similar science goals to space observatories, specifically high-resolution imaging—it will have the capability of seeing down to 30-kilometer scales—and detailed spectroscopy. It will be able to see the strange ways that magnetic field lines twist and braid themselves as well as how they mediate the flow of energy. Understanding these physical processes is a key step toward explaining how the solar wind—the outflow of gas that blows past Earth and has such a large effect on our atmosphere—is powered.

Stellar seismology is maturing rapidly. Analogous to Earth-based seismology, this technique enables astronomers to probe the deep interior regions of stars using the complex oscillations observed at the star's surface, much as the tone of a musical instrument reveals its internal construction. In the next decade, the rapidly increasing power of computers will allow us to take the known physical laws that are at play and synthesize them into detailed three-dimensional movies of the life and death of stars.

The life stories of stars can be strikingly changed if the star has a companion star orbiting in close proximity. One of the most dramatic examples of this occurs in a system containing a white dwarf star, which is the burnt-out core of a star like the Sun, with about as much mass as the Sun compressed into an object the

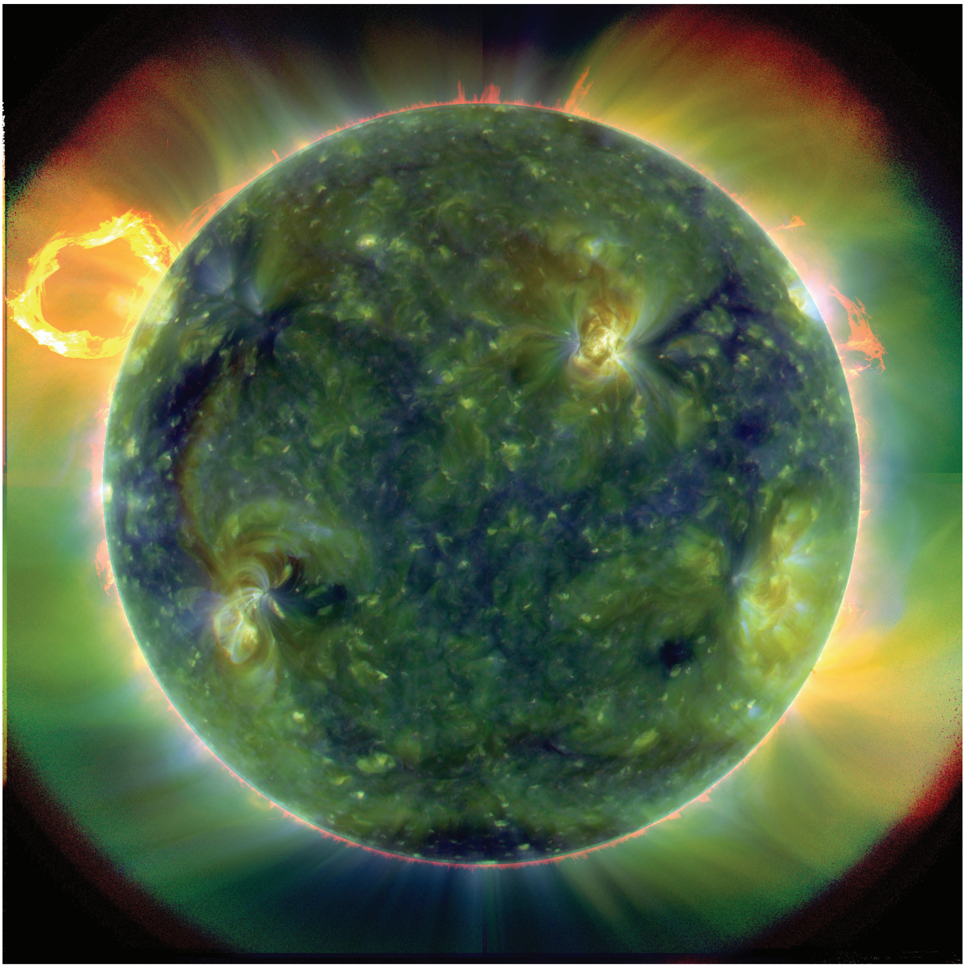


FIGURE 2.9 Solar Dynamics Observatory image of the Sun in the extreme ultraviolet. Different colors indicate different-temperature plasma, with hotter emissions traced from red to blue to green. SOURCE: NASA/SDO/AIA.

size of Earth. Mass transferred onto the white dwarf from its companion star can trigger a runaway thermonuclear instability and explosion, providing a light show that can be seen halfway across the universe. This type of supernova event is also the most important source of iron—from that in Earth's core to the hemoglobin in our blood—in the universe.

Stars more massive than about 10 times the mass of the Sun end their lives as supernovae when their deep interior has exhausted all energy supplies from nuclear fusion. Within fractions of a second, this energy crisis triggers a collapse of the innermost solar mass of material to densities so high that the nuclei of atoms are literally "touching." The rest of the star subsequently collapses onto the newly born neutron star, resulting in ejection of most of the star into the interstellar medium, spreading the products of millions of years of fusion reactions. Sometimes the collapsing material overwhelms the young neutron star, leading to a further collapse to a black hole.

Wide-field sky surveys during the next decade should reveal tens of thousands of these core-collapse supernovae per year and thus a diversity of stellar remnant outcomes much richer than currently known. Remarkable discoveries could occur if we are lucky enough to have a galactic supernova, as the overwhelming number of neutrinos from the young neutron star would provide an exciting probe of the competition between collapse and explosion going on in the inner 20 kilometers of these explosions. Even more remarkable would be to find direct evidence for gravitational wave emission from such a nearby explosion, a possibility for Advanced LIGO. Progress will also occur via continued theoretical and computational efforts, especially as three-dimensional simulations become computationally plausible. Finally, exploding stars leave remnants hypothesized to be the galactic particle accelerators that produce ubiquitous high-energy charged-particle cosmic rays, including those that crash into Earth's atmosphere, producing telltale radioactive isotopes. X-ray, gamma-ray, and radio observations of these stellar remnants will test this hypothesis and reveal the accelerator dynamics of the stellar ghosts (Figure 2.10).

Planetary Systems

Our Sun is just one of the several hundred billion stars in the Milky Way, and its well-ordered configuration of eight planets just one of the many diverse planetary systems. Although we have studied our solar system with telescopes for 400 years, we have only, in the past two decades, been able to detect planets orbiting other stars and begun to appreciate their astonishing diversity. We have uncovered surprises ranging from Earth-size planets orbiting the compact corpses of burned-out stars to planets termed "hot Jupiters" that are more than 100 times the mass of Earth but that are so close to their stars that they orbit them in just a few days. Models of the formation of planetary systems predict that planets this massive should form at much greater distances; these bodies have forced us to consider processes of "migration" that bring large planets closer to their stars early in their histories.

The details of how planets form within disks are still being revealed by current astronomical techniques, including imaging from Hubble, Spitzer, and the largest ground-based telescopes, plus theoretical studies including computer modeling. Disks start out being dominated by gas—the hydrogen and helium of the pri-

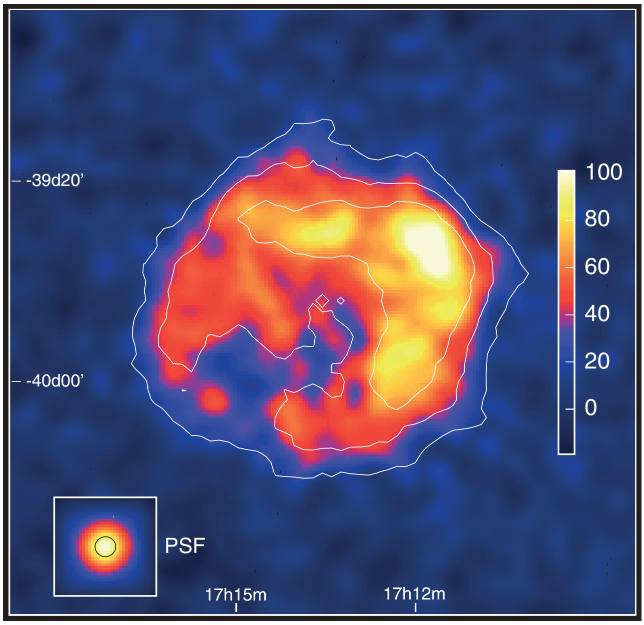


FIGURE 2.10 Supernova remnant RX J1713.7-3946 observed in the highest-energy tera-electron-volt (TeV) gamma rays. Recent observations using atmospheric Čerenkov telescopes have demonstrated that cosmic rays are accelerated to energies in excess of 100 TeV and that the magnetic field is amplified to high strength. Contours are X-ray emission. Supernova explosions like those that left behind this source created and dispersed heavy elements and also accelerated cosmic rays. SOURCE: The HESS Collaboration: F. Aharonian, A.G. Akhperjanian, A.R. Bazer-Bachi, M. Beilicke, W. Benbow, D. Berge, K. Bernlöhr, C. Boisson, O. Bolz, V. Borrel, I. Braun, F. Breitling, et al., A detailed spectral and morphological study of the gamma-ray supernova remnant RX J1713.7-3946 with H.E.S.S. Astronomy and Astrophysics 449(1):223-242, 2006, © ESO, reproduced with permission.

mordial cosmos salted with the heavy elements out of which planets and life are composed—and evolve with time into dusty disks or rings between the newborn planets themselves. While most if not all stars like our Sun may possess disks early in their histories, what fraction of these turn into planetary systems is not known, but the indications are that it is large.

Life

We have only the most rudimentary ideas about what conditions are necessary for and conducive to the formation of life. Even here modern astronomy has a key role to play, by finding and characterizing planets with the features that allow for life around stars other than the Sun. It will require study of individual planets by directly sensing their light to find the molecular signposts of habitability in the atmospheres and surfaces of these distant bodies.

This last task, possible now for nearby giant planets, is exceedingly difficult for Earth-size bodies with disks 100 times smaller in area than Jupiter's. The signature of water, together with a suitable orbit around a parent star, would tell us that the medium for life as we know it is likely present as a surface liquid. Methane indicates that organic molecules (the structural building block of life) are present; oxygen with methane would indicate a state of extreme chemical "disequilibrium" that could likely not be maintained in the absence of life.

The most promising signatures of life on planets around other stars are features in the atmospheric spectra of planets around other stars, such as the "red edge" arising from photosynthesis. Less definitive is molecular oxygen, which is locked up in oxidized surface minerals unless continually replenished either by life (as on Earth) or catastrophic loss of surface water followed by photolysis of water in the atmosphere (as on early Venus). The presence of both water and methane in a planetary atmosphere is a more reliable biosignature of water-based organic life than is the presence of one or the other alone. A different approach is to look for signals produced by technologically advanced entities elsewhere in our galaxy.

FRONTIERS OF KNOWLEDGE

New fundamental physics, chemistry, and biology can be revealed by astronomical measurements, experiments, or theory and hence push the frontiers of human knowledge.

Science frontier questions for advancing knowledge:

- ***Why is the universe accelerating?***
- ***What is dark matter?***
- ***What are the properties of neutrinos?***
- ***What controls the mass, radius, and spin of compact stellar remnants?***

One of the key insights of the past few centuries was the recognition that the same scientific laws that govern the behavior of matter and energy on Earth also govern the behavior of the cosmos: planets, stars, galaxies, and the entire universe. Newton inferred that the same physical forces causing apples to fall to Earth also govern the motions of the Moon around Earth and the planets around the Sun. One hundred and fifty years later it was discovered that chemical elements introduced into laboratory flames produced a unique set of spectral lines, and since many of these lines also appeared in the solar spectrum, it was concluded that the Sun was made of the same chemical elements as found on Earth, or as in the case of helium, a new one waiting to be discovered. Astronomers feel confident in using the universe as a laboratory to explore natural phenomena that are inaccessible to Earth-based laboratories. The study of how the universe and its constituent objects and phenomena work continues to yield unique insight into fundamental science.

The Nature of Inflation

As described previously, the inflation hypothesis proposes that the universe began to expand exponentially some 10^{-36} seconds after the big bang. This hypothesis explains why the present universe has almost the same temperature everywhere we look, as measured by the microwave background radiation, over the entire sky. Despite the power of the hypothesis, the mechanism by which inflation happened—its origin—remains a great mystery. Directly confirming inflation and understanding its fundamental underlying mechanism lie at the frontier of particle physics, because inflation probes scales of energy far beyond anything that can be achieved in accelerators on Earth. Inflation is central to astrophysics: the quantum fluctuations present during inflation formed the seeds that grew into the CMB fluctuations and the large-scale structure of the universe we see around us today. Perhaps the most profound reason to understand inflation is that its nature and duration might have spelled the difference between a universe of sufficient vastness to house galaxies, planets, and life, and a "microverse" so small that matter as we know it could not be contained therein. To understand the origin of our macroscopic universe—why we exist—requires understanding inflation.

The last decade was one of stunning progress in our understanding of the first moments of the universe. NSF-supported South Pole and Chilean ground-based work, and NASA's balloon-based studies and the Wilkinson Microwave Anisotropy Probe Explorer mission, mapped the spatial pattern of temperature fluctuations that occur in the relic cosmic microwave background from the big bang. The state of the young universe during the epoch of inflation, prior to the existence of stars or galaxies, is imprinted as minute fluctuations in the CMB, and the character of these fluctuations is broadly consistent with the theory of inflation. Armed with theoretical advances and complementary balloon-borne and ground-based measurements, we are now ready to move beyond foundational knowledge of the very early universe and apply increasingly more precise measurements of the CMB to new questions. One important test of inflation involves making highly detailed measurements of the structure of the universe by mapping the distribution of hundreds of millions of galaxies. Inflation makes very specific predictions about the spatial distribution of the dark matter halos that host these galaxies.

However, the most exciting quest of all is to hunt for evidence of gravitational waves that are the product of inflation itself. Just as the light we see with our own eyes can be polarized, the CMB radiation may also carry a pattern of polarization—

the so-called B-modes—imprinted by inflationary gravitational waves. Different models of inflation predict distinguishable patterns and levels of polarization, and so the next great quest of CMB research is to detect this polarization, thereby probing the behavior of the particles or fields driving inflation.

Today we stand at a crossroads. If we discover the signature of inflation in the CMB in the next few years, future studies would focus on follow-up precision measurements of that signal. If, on the other hand, the signal is not seen, then we will need to develop different approaches that may ultimately lead us to revise our theoretical models. More detailed measurements of the CMB are a path to exciting future discoveries—fed by both technology development and theoretical inquiry.

The Accelerating Universe

About 12 years ago, the simple picture of a universe decelerating because of gravity began to fall apart. Due in large part to supernova distance measurements, we have since come to realize that instead of decelerating, the expansion of the cosmos is accelerating. Why this is so is an outstanding puzzle in our modern picture of the universe.

The observation that the universe is accelerating is at present consistent with Einstein's postulate of a cosmological constant or equivalently with the idea that empty space carries energy. It is also consistent with the more general idea that space-time is permeated with gravitationally repulsive dark energy, a mysterious substance that accounts for more than 70 percent of the energy content of the universe. Alternatively, cosmic acceleration could be an indication that Einstein's theory of gravity—general relativity—must be modified on large scales. In Einstein's theory, the growth of structure and the expansion of the universe are linked by gravity; in modifications of gravity, that link is altered.[5] Understanding the underlying cause of acceleration therefore requires precision measurements of the expansion of the universe with time and of the rate at which cosmic structure grows. Comparing the expansion history of the universe with the history of the growth of structure will in principle enable us to test whether dark energy or modifications of general relativity are responsible for cosmic acceleration.

Fortunately, the supernova distance measurement techniques are advancing dramatically, and a few other independent techniques are being developed that also promise advances in precision measurement of the expansion history, as well as adding measurements of the growth of structure. Knowing how the size of the universe changes with time means that we can now chart the rate at which the universe grew over its long history. By combining all these data we can test whether the

[5] The extremely small value of a cosmological constant that would be consistent with the observed acceleration is not a natural fit for current physics theories.

theory of relativity is correct and also determine whether Einstein's cosmological constant gives an accurate description of the way dark energy determines the fate of our universe.

The Nature of Dark Matter

"Normal" matter—the stuff of which we, Earth, and the stars are made, as well as the more exotic particles created in Earth-bound accelerators or in natural accelerators such as supernova remnants—appears to be only a minority of the matter in the cosmos (Figure 2.11). This discovery through measurements of the rotation rate of galaxies was presaged by work as early as the 1930s in which astronomers noticed that the speeds at which galaxies orbit around the centers of the clusters to which they belong are far higher than needed to counteract the gravitational pull of the stars in those clusters. To keep these clusters from rapidly flying apart, astronomers argued, they must contain far more material than that visible to telescopes. A lot of astronomical detective work ruled out the hypothesis that the invisible mass might simply be unobservable planets and dead stars, and so it became known as a mysterious dark matter.

By now, the evidence for such dark matter in almost all galaxy-size and larger astronomical systems is overwhelming and comes from a wide variety of techniques—among others, gravitational lensing measured by the Hubble Space Telescope and ground-based telescopes, the distribution of hot X-ray-emitting gas

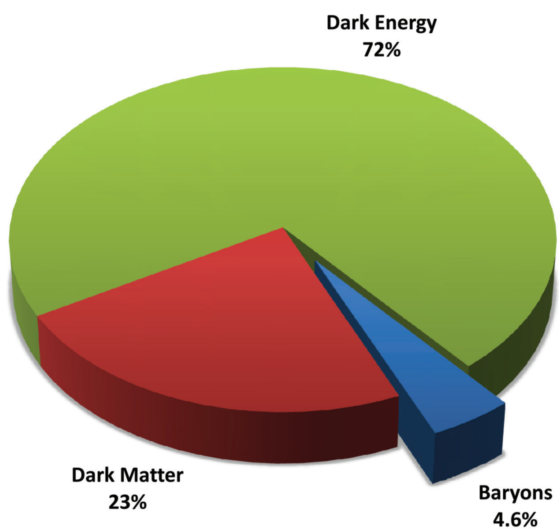


FIGURE 2.11 The current composition of the universe; "normal" (baryonic) matter is less than 5 percent of the total.

measured by the Chandra X-Ray Observatory, and the rotation speed of hydrogen gas disks surrounding galaxies measured by ground-based radio telescopes (Figure 2.12). With improved observations, astronomers have determined precisely how much dark matter there is, and learned that it interacts only with itself and very feebly with familiar matter only through gravity. These normal-matter constituents are small islands in a vast sea of dark matter of some unknown form.

An important clue to the nature of dark matter comes from indirect but powerful arguments based on the formation of the elements and the formation of galaxies. It has been found that only one-sixth of the total matter is in normal "baryonic" form and that the remainder is probably some exotic new elementary particle generated in copious quantities in the big bang but not yet detected by Earth-based particle accelerator experiments. If so, elucidating the nature and properties of the dark matter particle (or particles) will open an entirely new window to our understanding of the fundamental properties of matter.

The hunt for dark matter is the joint domain of elementary particle physics, astrophysics, and astronomy. Circumstances in all arenas are ripe for the detection of dark matter in the coming decade. Some of the most promising candidate dark matter particles predicted by theorists have properties that imply they will be produced anew in experiments at the Large Hadron Collider (LHC), while relic copies from the early universe will be detected at high energy from their self-interactions or decay in space, producing gamma rays and other high-energy particles, and at low energy in experiments at deep-underground laboratories where rare collisions occur between normal atoms and the sea of galactic dark matter particles through which Earth swims. Already, important constraints have been set on the nature of dark matter through the failure to detect it using underground detectors and the Fermi Gamma-ray Space Telescope. This is a great period of interdisciplinary convergence in the quest to understand the nature of dark matter.

The Nature of Neutrinos

Neutrinos (a type of elementary particle) interact very weakly with other matter. Because of this property, even massive bodies such as stars are transparent to neutrinos. The detection of neutrinos produced in the center of the Sun provided a direct confirmation of the nuclear reactions occurring there, and the ~20 neutrinos detected from a supernova explosion in a nearby galaxy in 1987 confirmed that the core of this massive star had collapsed to densities comparable to that of an atomic nucleus (likely forming a neutron star). More remarkably, over the past decade, observations of neutrinos produced by cosmic rays striking Earth's atmosphere, and more refined detections of solar neutrinos, demonstrated that the three known types of neutrinos can oscillate from one type to another. This discovery implies that the neutrino mass, though small, is non-zero and offers direct proof that the

FIGURE 2.12 *Upper:* Hubble Space Telescope observations of a gravitational lens discovered in the Sloan Digital Sky Survey database by the Sloan Lens ACS Survey. Light from a distant blue galaxy (*upper right, top*) is deflected by the gravitational field of an intervening elliptical galaxy (*upper right, center*) to give an image in the form of a nearly complete "Einstein ring" (*upper right, lower*). By analyzing the combined image (*upper left*) it is possible to learn about the distribution of dark and luminous matter in the elliptical galaxy as well as create a magnified image of the background source galaxy. SOURCE: A. Bolton for SLACS and NASA/ESA.

Center: The inferred dark matter distribution in the interacting galaxy cluster 1E 0657-56 is shown in blue, compared to the measured hot X-ray-emitting cluster gas in red and the visible light from individual galaxies in the optical image. In this classic example, the dark matter mass dominates the radiating, baryonic mass. SOURCE: X-ray—NASA/CXC/CfA/M. Markevitch et al.; Optical—NASA/STScI, Magellan/University of Arizona/D. Clowe et al.; Lensing map—NASA/STScI, ESO WFI, Magellan/ University of Arizona/D. Clowe et al.

Lower: THINGS survey, undertaken at the NRAO's Very Large Array (VLA), of atomic hydrogen in nearby spiral galaxies, showing complex and extended gas distributions. SOURCE: NRAO/AUI and Fabian Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, and R. Kennicutt.

standard model of particle physics is incomplete. Indeed, astrophysical research has provided much of the evidence for physics beyond the standard model.

Our ability to probe the fundamental properties of neutrinos by using astrophysical measurements will continue in the coming decade. The neutrino oscillation measurements of the past decade probed only the difference in the squares of the neutrino masses, not the absolute masses, and we currently have only upper limits on the actual masses. Neutrinos were produced in abundance in the big bang, and although they constitute only a minor component of the dark matter, they affected the clustering of matter on large scales in a way that depends on their mass. Thus, the determination of the masses of the neutrinos—fundamental input to theories of the very small—may come from observations of the very large. In the coming decade, precise measurements of the structure seen in the CMB combined with measurements of large-scale structure from the next generation of visible/infrared imaging and spectroscopic surveys plus X-ray observations of clusters of galaxies will allow us to measure the neutrino mass or push its upper limit downward by an order of magnitude, and thereby help constrain particle physics models governing the behavior of all mass.

The Nature of Compact Objects and Probes of Relativity

Astronomical observations have verified that general relativity provides an accurate description of gravity on solar system scales, but an unanswered question, and the most challenging test of general relativity, is whether it works in the strong gravity fields around black holes. Current studies using X-ray spectroscopy of gas disks around black holes are consistent with the predictions of general relativity and yield preliminary estimates of the black hole spin. Over the next decade the precision of these tests can be dramatically improved.

Also feasible within the decade is the detection of gravitational waves from mergers of million-solar-mass black holes or low-mass objects captured by more massive ones. Such events produce clean signals that can be used to map space-time with tremendous precision in regions where gravity is very strong. An important theoretical and computational breakthrough in this decade was the ability to compute the merger of two black holes, yielding highly accurate predictions of the gravitational wave emission patterns. Combined with detections of these waves, such computations provide stringent tests of the theory of relativity in regimes not accessible by any other means. Deviations from Einstein's predictions would cause us to rethink one of the foundational pillars of all of physical science.

Gravitational wave detection would not only test general relativity but also measure the spins and masses of the merging black holes. Furthermore, the discovery and understanding of such merging systems would uniquely probe the conditions at the centers of galaxies and the cosmological history of galaxy formation and growth. Black holes are common in the centers of galaxies, and our estimates of their abundance, masses, and merger rate are poised for steady improvement in precision through a space-based interferometer that can reach back in time to "hear" the space-time echoes of mergers of supermassive black holes.

Observations with X-ray telescopes provide a complementary probe of the nature of space-time near the event horizon at the edge of a black hole. Such observations allow us to track the motions of material as it swirls "down the drain," and thereby to measure the spin of the black hole. This is currently possible only for a handful of nearby black holes, but more powerful facilities in the future would enable us to extend these measurements to large samples. Since any black hole can be fully characterized by its mass and spin, this is fundamental information about how black holes work and how they were formed.

Yet another probe of black holes is the jets that are frequently created by massive spinning black holes in active galactic nuclei. Radio telescopes have shown that the emitting gas travels with speeds close to that of light. X-ray and now gamma-ray telescopes are able to trace the emission down to quite close to the black hole itself. Plasma and magnetohydrodynamic physics, which we understand best from solar and solar system studies, play important roles in many astrophysical contexts. It is proposed to combine the results from many types of telescopes operating simultaneously to understand how jets are made and how they shine. This will then lead to a better understanding of how gravity operates around a black hole. Black holes—either spinning massive holes in active galactic nuclei or newly formed stellar ones in gamma-ray bursts—are also suspected to be the source of the ultrahigh-energy cosmic rays that are detected when they hit Earth's atmosphere. These can have energies as large as that of a well-hit baseball, but despite the great advances in understanding of their properties that have come from the Auger-South facility in Argentina, we still do not know for sure what they are, how they interact with matter, and how they are made.

Only slightly less remarkable than black holes are the neutron stars. It is with respect to neutron stars that the investments over the last decade in ground-based gravitational wave detectors are likely to pay off first, given that frequent detections of merging neutron stars in other galaxies are expected from Advanced LIGO. Formed as the catastrophic collapse of the core of a dying massive star, these amazing objects contain a mass larger than the Sun's, squeezed into a region the size of a city. The centers of neutron stars contain the densest matter in the universe, even more tightly compressed than the matter inside the nucleus of a single atom. Some neutron stars also have the largest inferred magnetic field strengths in the universe, a thousand trillion times larger than that of Earth.

Studying the properties of neutron stars offers a unique window into the properties of nuclear matter. Measuring neutron star masses and radii yields direct information about the interior composition that can be compared with theoretical predictions. Studies of young radio pulsars and the remarkable magnetar subclass have revealed that as many as 1 in 10 neutron stars, which have descended from normal stars, are born with magnetic fields that exceed 10^{14} times that of our Sun. What sets this fraction, and whether or not the birth of these highly magnetic neutron stars visibly alters the supernova event, are being actively investigated. Progress here will depend on large surveys of supernovae as well as continued radio and X-ray pulsar observations. The most rapidly rotating neutron stars appear to spin on their axes about once every 1½ milliseconds, by accreting material from a rapidly rotating disk of matter donated from a companion star. However, ever more sensitive radio pulsar surveys continue to find that the maximum spin rate observed is surprisingly less than the maximum possible value, leading to the speculative suggestion that gravitational wave emission regulates the maximum rate. This hypothesis is testable with Advanced LIGO.

The Chemistry of the Universe

Many astrophysical processes exhibit rich chemical signatures and products. The cycle of matter in our galaxy proceeds from the expulsion of matter into interstellar space from dying stars, where it undergoes chemical transformations and eventual incorporation into diffuse clouds and dense molecular clouds. Well over 140 molecules, rich in organic material, have been detected in the interstellar medium by radio, microwave, and infrared techniques, and this is almost certainly the tip of the interstellar chemical iceberg (Figure 2.13). Thanks to the diverse range of interstellar energy sources and environments to which such molecules are exposed, we have the opportunity with ALMA and SOFIA to study fundamentals of chemistry under conditions we cannot create here on Earth.

ALMA will greatly increase our ability to probe the chemistry of nearby galaxies. On a cosmological scale, the chemistry of the primordial elements hydrogen, helium, and lithium was surprisingly rich and dictated the early-universe interactions between matter and radiation. Molecular hydrogen was possibly crucial in forming the first stars after recombination, and studies of redshifted spectra of neutral atomic hydrogen may provide information concerning molecular hydrogen by observing density inhomogeneities. Observations of molecular spectra can give us unique probes of the density, temperature, and kinematics of regions where stars and planets are formed. Exploration of the chemistry in high-redshift galaxies is a current challenge that, as it is met, will provide us with a picture of the evolution of molecular reactions and species across cosmological time.

Tracing the history of organic molecules through their cycles of formation, modification, destruction, and reformation often on the surfaces of tiny dust grains within molecular clouds to their incorporation in planetary systems is important

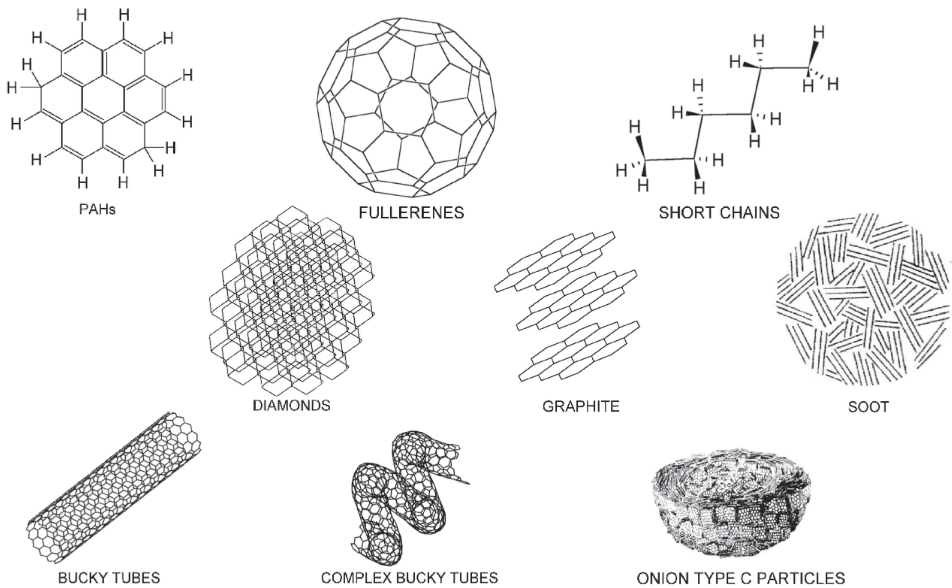


FIGURE 2.13 Some of the many forms that carbon might take in interstellar molecules. SOURCE: P. Ehrenfreund and S.B. Charnley, Organic molecules in the interstellar medium, comets, and meteorites: A voyage from dark clouds to the early Earth, Annual Review of Astronomy and Astrophysics 38:427-483, 2000.

in understanding where and in what form are the raw materials for life with which any given planetary system might be endowed (Figure 2.14).

To what extent does the potential for life change through the galaxy over its history? We do not understand the ultimate levels of complexity achieved by organic chemistry in astrophysical environments, for example, whether complex information-carrying polymers like ribonucleic acid might be produced before planet formation. Study at ever more powerful spectral and spatial resolution of astrophysical environments in which organic molecules occur and evolve is necessary to trace the full potential of organic chemistry to produce molecules of relevance to life, through as much of the galaxy as is possible. Such environments include the interstellar medium, molecular clouds, protoplanetary disks, transition and debris disks, and especially planetary atmospheres. And this, in turn, brings us full circle in our tour of the modern understanding of the cosmos: the exotic phenomena of the earliest moments of the cosmos set the stage for a physical reality in which stars, planets, and life—we—could exist.

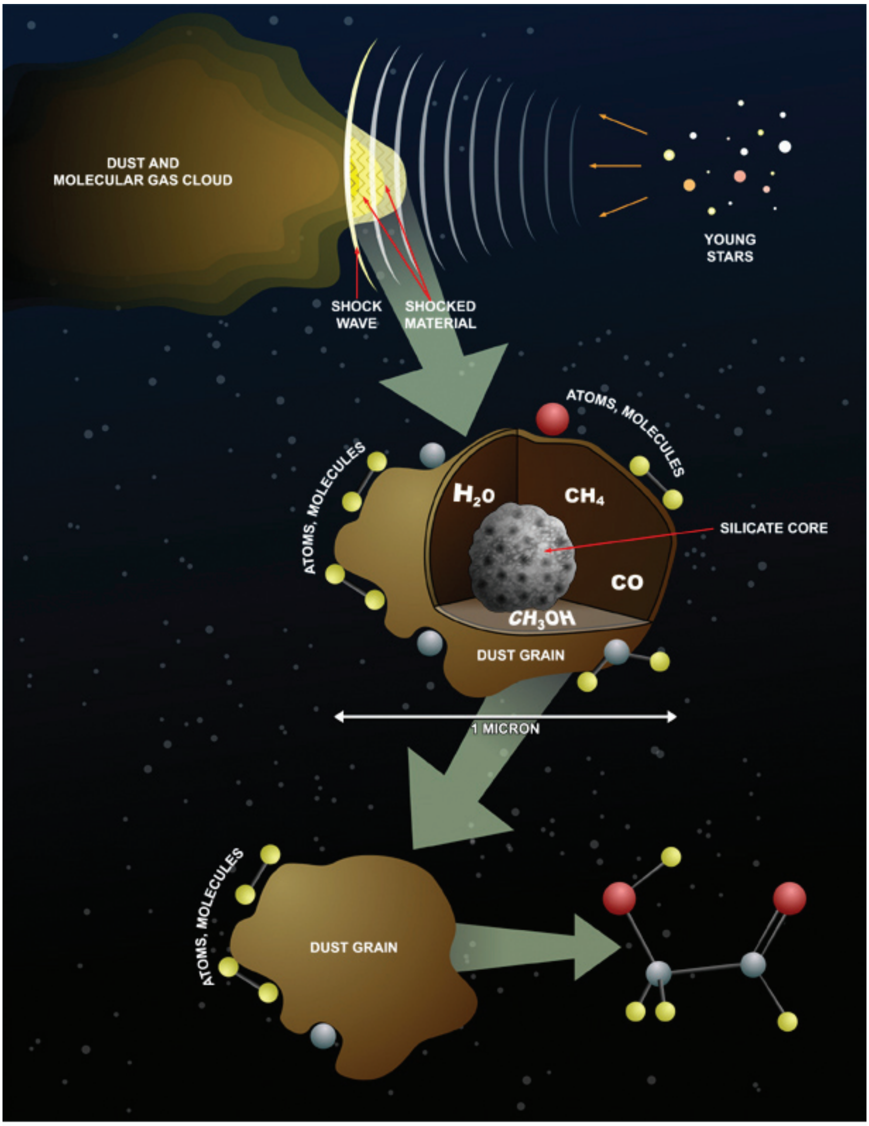


FIGURE 2.14 Shown here is a possible pathway toward making the sugar molecule glycoaldehyde, which was detected by the NRAO Green Bank Telescope in the Sagittarius B2 cloud of gas and dust. Material expelled from the vicinity of forming stars collides with a nearby molecular cloud (such as Sagittarius B2), generating shock waves. The heating associated with the shock allows chemical reactions to occur among atoms and small molecules that are embedded on the surfaces and in the interiors of small grains in the cloud. The resulting larger molecules that are formed, such as glycoaldehyde, are ejected from the grains thanks also to the shock waves, and end up in the surrounding gas where they can be detected. The red atoms are oxygen; the grey, carbon; and the yellow, hydrogen. SOURCE: Bill Saxton, NRAO/AUI/NSF.

3

Partnership in Astronomy and Astrophysics: Collaboration, Cooperation, Coordination

Fifty years ago, just before the first decadal survey in astronomy (the Whitford report), astronomy and astrophysics was practiced very differently than it is today. Virtually all telescopes were in private hands and viewed the sky in just the visible part of the spectrum using photographic plates or early photomultiplier tubes to record data; radio astronomy was still a new technique; the great potential of space was only beginning to be discussed. The United States dominated astronomical research. Federal support was small and existed only at NSF; NASA was soon to begin its race to the Moon and consider its first astrophysics missions. The frontiers were large and inviting. Many of the most phenomenal discoveries of the century lay ahead. Neutron stars, black holes, quasars, exoplanets, dark matter, dark energy, and the cosmic microwave background were yet to be found. Astronomy was a somewhat insular field, and its connection to physics, principally through atomic and nuclear physics, was just starting to grow.

Since that time, astronomy has been in a period of revolutionary discovery—from stars and planets to black holes and cosmology—and is poised for dramatic advances in our understanding of the universe and the laws that govern it. There are strong and growing connections to other fields, including physics, computer science, medicine, chemistry, and biology. Few today would refer to astronomy as an island in the world of science.

Advances in technology have propelled much of the change. Digital devices with hundreds of millions of pixels have enabled wide-field images and massively multiplexed spectroscopy at optical and infrared wavelengths. Radio technology has progressed to the point where sensitive, high-resolution images and spectra are routinely available. A panoply of detectors has provided astronomers with microwave, infrared, ultraviolet, X-ray, gamma-ray, cosmic-ray, neutrino, and gravitational radiation eyes—allowing the universe to be observed in a rich variety of ways. Many of these new windows on the universe were made possible by the ability to place increasingly sophisticated observatories in space—from the pioneering COBE, IRAS, Copernicus, UHURU, SAS-3, and Compton-GRO to WMAP, Spitzer, Hubble, Chandra, Fermi, and Swift today. Over this same period, computing power has increased by 10 orders of magnitude in both processing speed and storage, racing through the petascale, and the exponential growth of digital bandwidth has revolutionized communications and the way science is done. Together, these techniques have provided new views that both solve old puzzles and uncover new surprises.

The sociology of astronomy has also changed. The field is more collaborative, more international, and more interdisciplinary. The style of carrying out research is different. Multi-wavelength approaches are necessary for many important problems. Observational data often come via e-mail or the Web, from space- and ground-based telescopes alike. The secondary use of data from archives, especially surveys, has grown in importance and in some cases even dominates the impact of a facility. In addition, breakthroughs are still made with great, imaginative leaps from our youngest scientific minds.

Because of the strong and important connections of astronomy to other disciplines, federal funding now involves five divisions at NSF—Astronomy (AST), Physics (PHY), Office of Polar Programs (OPP), Atmospheric and Geospace Sciences (AGS), and the Office of Cyberinfrastructure (OCI)—as well as the Astrophysics, Heliophysics, and Planetary Science Divisions at NASA, the Office of High Energy Physics (OHEP) and the Office of Nuclear Physics (ONP) at the Department of Energy, and the Smithsonian Institution. At the same time that federal support has grown and diversified, private funding of large ground-based observatories has increased as well.

Optimizing the federal investment in astronomy must take account of the changing scientific, sociological, and funding landscape. This presents new challenges—from data acquisition and access to interagency and international coordination. This chapter addresses the interfaces between different partners and makes recommendations on how to optimize the federal investment in astronomy at this time of revolutionary discovery about our place in the universe.

INTERNATIONAL PARTNERSHIPS

The Globalization of Astronomy

For much of the 20th century, research in astronomy was dominated by the United States. Today, the globalization that has influenced so many facets of our society is transforming astronomy as well—see Box 3.1. Over the past 50 years astronomy has expanded dramatically in Europe, which has achieved parity with the United States in many areas, as well as in Australia. A similar, more recent expansion in Asia—Japan and China in particular—is likely to influence the future of our subject for decades to come (Figure 3.1). South America also continues to increase its impact on the field, and South Africa is becoming a presence. In this new era it is imperative that planning for the U.S. research enterprise be done in an international context. We all share one sky and similar science agendas, and there are significant gains to be made by increasing international coordination and cooperation. This is a challenging task, because our early leadership means that many U.S. researchers, institutions, funding agencies, and policy makers are unaccustomed to long-range scientific planning with an international perspective.

Astronomy is among the most international of research disciplines, in part because the best ground-based observing sites (e.g., Antarctica, Australia, Chile, Hawaii, southern Africa), and of course space, are not necessarily located in places with the largest human and fiscal assets. Although the U.S. investment in astronomy has grown, that of the rest of the world has grown even faster. While this outcome should be celebrated, it does underscore that it is no longer possible for the United States or any other country to assume that it is an unquestioned leader across the whole field. Given the growing scale, cost, and complexity of major projects and the convergence of national scientific agendas, astronomy is becoming increasingly collaborative and cooperative—essential and desirable features for the field in the 21st century.

As astronomy research has blossomed in recent decades, the complexity has grown proportionately, as has the expense of the facilities necessary to explore the universe. The launch of the Hubble Space Telescope (HST) marked the entry of astronomy into large-scale transformative scientific facilities. A salient feature of the HST and other large space facilities in this class, such as Chandra, Fermi, Herschel, Kepler, Planck, Spitzer, and XMM-Newton, is that many are collaborative with other nations. The same is true of recent large ground-based astronomy and astrophysics facilities such as the NSF-funded Gemini telescopes, LIGO, and IceCube, and the NSF/DOE astrophysics projects Dark Energy Survey (DES), Auger, and VERITAS. The forthcoming flagships of the 2001 decadal survey AANM[1]—JWST

[1] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

BOX 3.1
The Modern Landscape

- In 2009, U.S. astronomers accounted for 25 percent of the total membership of the International Astronomical Union, the major international society of professional astronomers; this fraction has declined over the past 10 years.
- The fraction of papers in major astronomy journals from U.S. authors was 42 percent in 2009; because of the growing number of non-U.S. papers there has been a slow but steady decrease in this fraction since 1980, when it was 67 percent.
- U.S. astronomers have access to 47 percent of the total world aperture in large optical telescopes (square inches of glass for the 17 telescopes with >6-meter aperture). Europe, with its Very Large Telescope (VLT; four 8-meter telescopes and an array of smaller telescopes used for infrared interferometry) at the European Southern Observatory (ESO) and new Grand Telescopio Canarias (11 meters), has achieved parity with the United States in ground-based optical and infrared astronomy.
- Although aperture is important for radio telescopes, angular resolution and frequency coverage are as important. For all three parameters, U.S. radio facilities are the equal of or exceed their foreign counterparts at centimeter wavelengths. The Expanded Very Large Array is by far the dominant centimeter-wavelength telescope in the world, and will remain so until the Square Kilometer Array is built. At millimeter wavelengths Europe's IRAM telescopes will remain the most powerful in the world, until the completion of the Atacama Large Millimeter/submillimeter Array (ALMA).
- Among ground-based telescopes that led to the most influential papers, defined as those with 1,000 or more citations, in 2001-2003 U.S. facilities contributed to 53 percent of the cited papers; for space-based telescopes the corresponding U.S. fraction was 63 percent.
- European funding of astronomy adopts accounting conventions that complicate direct comparisons with U.S. funding of astronomy. However, it can be noted that ESO, with its annual budget of roughly $175 million, has constructed the four 8-meter VLT

in space and ALMA on the ground—are also international partnerships. Perhaps the most telling measure of the growing influence of globalization in astronomy projects is the fact that nearly all of this report's ranked recommended projects have opportunities for contributions—often substantial—by foreign partners.

Managing International Collaboration

Thanks to the growth of astronomy across the globe and the emergence of international partnerships on all scales—from individual scientific collaborations to major multinational projects and sharing of major data sets—science agendas around the globe are converging. At the same time, the growth in the costs and complexity of new telescopes and instruments is pressing the need for expanded international cooperation at all stages, from conceiving and building to using and is an equal partner with North America (including the United States, Canada, and Taiwan) in 75 percent of ALMA (Japan is a 25 percent partner). ESO is now aggressively planning a 42-meter European Extremely Large Telescope (E-ELT), which is significantly larger than the Giant Segmented Mirror Telescope planned for completion in 2018. Investments in the SKA being made by Europe, South Africa, and Australia far exceed those of the United States. In space astronomy, the European Space Agency has just launched the successful Herschel and Planck telescopes with a combined cost of more than $2 billion and is planning its next Cosmic Vision missions.

- Astronomy planning exercises are now conducted around the world. The European Union recently completed its first decadal survey in astronomy, the ASTRONET study,[1] and similar activities have been conducted for European astroparticle physics (ASPERA)[2] and space astronomy.[3] Australia's 10-year (2006-2015) strategic plan[4] strongly emphasizes international partnerships for the largest projects. Although there is remarkable convergence on the most compelling science questions and considerable overlap in plans for facilities, there is relatively little or no formal international input to or coordination between these activities.
- Additional, major international activities include those involving Australia (e.g., Gemini partner, SKA precursor programs), Japan (e.g., JAXA, Subaru), and China (e.g., FAST).

[1] For more information on the ASTRONET survey and its reports, see http://www.astronet-eu.org/.

[2] For more information on ASPERA (Astroparticle ERAnet), see http://www.aspera-eu.org/.

[3] European Space Agency, Cosmic Vision: Space Science for Europe 2015-2025, *ESA Brochure,* BR-247, October 15, 2005, available at http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=38542.

[4] National Committee for Astronomy of the Australian Academy of Science, *New Horizons: A Decadal Plan for Australian Astronomy 2006-2015,* November 2005, available at http://www.atnf.csiro.au/nca/DecadalPlan_web.pdf.

these precious instruments. These pressures are most evident in ground-based facilities. The advantages of such partnerships are manifest: cooperation can reduce unnecessary duplication of facilities and effort, marshals the best technological expertise globally, provides international merit-based use of the facilities, and makes it possible to construct facilities that otherwise would be out of the financial reach of any one nation or region.

Traditional international partnerships, in which two or more national partners collaborate in the construction, operation, and management of a facility, also carry with them inherent disadvantages and overheads. The involvement of multiple organizations inevitably increases the complexity of decision making and management, which translates into a significant overhead in project costs. If government agencies are involved, either as direct partners or as managing agencies for one or more partners, the increase in bureaucratic requirements and the delays in decision

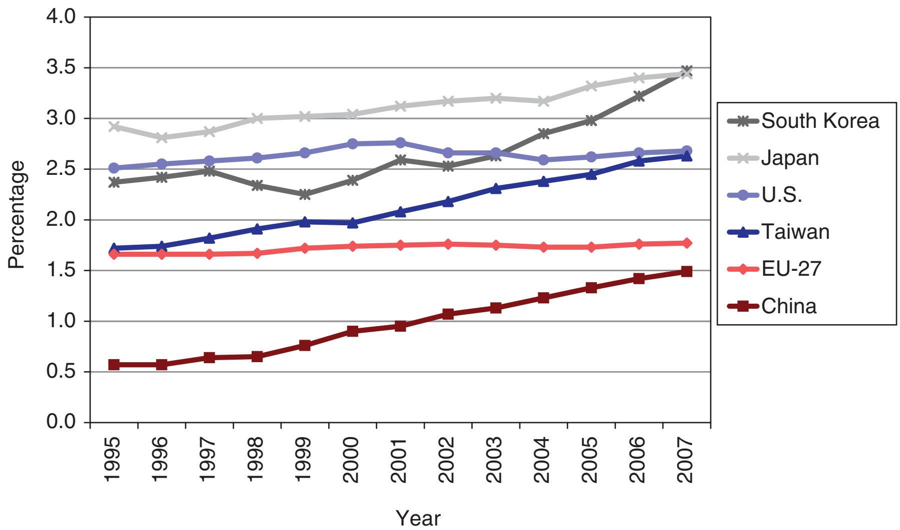


FIGURE 3.1 Illustration of the expansion in overall investment (percent of gross domestic product) in research and development by Asian countries, in contrast to the relatively flat investment over the past decade by the United States and Europe. SOURCE: American Association for the Advancement of Science, R&D Budget and Policy Program. © 2010 AAAS.

making can be even more severe. The presence of additional approval layers can hinder the ability of a project to respond to changes in performance and cost that often occur during the development of a facility. Legal requirements such as the U.S. International Traffic in Arms Regulations (ITAR) can add significant delays and costs. Finally, international commitments can make it much more difficult to terminate or descope projects but can also smooth out funding profiles if partners are able to contribute at different times or rates. Overall, the implied financial stability of government agency involvement can be a double-edged sword.

An alternative approach to partnership is to coordinate access across a suite of facilities. In this model, individual parties build or operate an instrument or facility but access and/or data rights are shared with partner communities. A more limited form of partnership is the sharing of archival data from a facility, even in cases where observing time is restricted. Other arrangements may prove to be just as effective. For example, access to both the northern and southern skies is essential for many areas of astronomy; a partnership could take the form of time swaps on solely owned telescopes in the two hemispheres. Likewise, one international partner might have a unique facility (e.g., the proposed Large Synoptic Survey Telescope), and access to its observing time or data could be traded for access to other unique facilities (e.g., VLT or E-ELT). The key advantage of such arrangements is that they foster merit-based scientific exploitation of the facilities, while minimizing the cost and administrative overheads that are inherent in a fully shared and managed project. The principle of open skies is compatible with the guiding principle of maximizing future scientific progress. In an increasingly international arena, flexibility will be a key to optimizing the science return from U.S. investments in new facilities.

A prerequisite for a successful partnership is that all parties view the arrangements as being fair and equitable, at least when considered across the sum of shared facilities. For example, under NSF's open skies policy, access to the U.S. national centimeter-wavelength telescopes (EVLA, GBT, VLBA, and Arecibo), which are the premier facilities in the world at these wavelengths, is allocated without regard to nationality. As a result, overseas investigators make substantial use of those facilities, accounting for typically one-third (for the NRAO telescopes; less for Arecibo) of the allocated observing time. At present, it can be said that U.S. researchers have enjoyed open access to many, though not all, premier international facilities. In addition, private U.S. telescopes do not, as a matter of course, allow open access to the full U.S. community, let alone foreign astronomers. However, the astronomical community does get access to ground-based optical infrared facilities through the Telescope System Instrument Program scheme.

Such imbalances are likely to arise, and when they do, it is incumbent on the agencies and observatory directors to take corrective action. For example, when the fraction of foreign users of a U.S. facility becomes very large, then this can be taken as a sign that the science from that facility is less aligned with U.S. national priorities or that the balance between support of U.S. facilities and the U.S. user community has gotten out of line. Likewise, if a serious asymmetry develops between the United States and foreign facilities, then that is the time to propose reciprocal arrangements that will preserve the principle of open skies. There are two caveats to this approach. For "open skies" and similar arrangements to work, they need to be seen to be symmetrical and fair in terms of scientific opportunity and cost recovery over the long run and averaged over many facilities.

An important goal for the U.S. agencies is to place appropriate value on reciprocity arrangements in providing access to foreign astronomical facilities and data sets for U.S. researchers. To encourage reciprocal arrangements for broad merit-based access to telescopes worldwide, the observing rights and access to survey data, e.g., during validation periods, could be restricted for U.S.-funded facilities to scientists at U.S. institutions, any foreign partners, and other parties with such reciprocity agreements. In any restriction of access to U.S. facilities, care must be taken to address the needs of scientists from countries whose ability to participate in the construction and support of expensive international facilities is limited.

RECOMMENDATION: U.S. investors in astronomy and astrophysics, both public and private, should consider a wide range of approaches to realize participation in international projects and to provide access for the U.S. astronomy and astrophysics community to a larger suite of facilities than can be supported within the United States. These approaches could include not only shared construction and operation costs but also strategic time-sharing and data-sharing agreements. The long-term goal should be to maximize the scientific output from major astronomical facilities throughout the world, a goal that is best achieved through opening access to all astronomers.

International partnership should be regarded as an element of a broader strategy to coordinate construction and support of and access to astronomical facilities worldwide and to build scientific capability around the world.

International Strategic Planning

Beyond the arena of science coordination and shared access to individual facilities, greater international consciousness and coordination in the planning of the future astronomical agenda as a whole are increasingly evident. The European scientific community has initiated international planning on a pan-European scale over the past 5 years, with its ASTRONET[2] and ASPERA (Astroparticle ERAnet), and the European Space Agency (ESA) Cosmic Vision exercises. These and similar plans from other communities are loosely modeled after the NRC decadal survey process, but up to now have not interacted to any substantive degree with the planning in the United States or elsewhere. Recognizing the potential value of international coordination and planning, the Organisation for Economic Co-operation and Development (OECD) Global Science Forum and the International Astronomical Union have sponsored workshops and other activities for the planning of future large facilities. The NRC's Board on International Scientific Organizations also recently held a symposium to bring scientists together with program managers and governmental ministers from around the world to discuss plans for the future.[3]

Although one might well envisage a time later in this century when the exercise embodied in this Astro2010 activity is carried out by an internationally organized committee under the sponsorship of all member agencies, it is far too soon to

[2] For more information on the ASTRONET survey and its reports, see http://www.astronet-eu.org/.

[3] The U.S. National Committee for the International Astronomical Union (IAU) worked with the National Research Council's Board on International Scientific Organizations, Board on Physics and Astronomy, and the Space Studies Board to host the symposium "Beyond the Decade: The Future of International Astronomy. A Celebration of the International Year of Astronomy," held on October 9, 2009, in Washington, D.C.; see http://sites.nationalacademies.org/PGA/biso/ IAU/PGA_053106.

recommend such a radical transition in planning. So long as the major share of astronomy research in the United States is underwritten by U.S. government agencies, it is clear that the research agenda and project recommendations ought to be determined at the national level. However, as more major projects—including nearly all of the very large scale astronomy and astrophysics projects—are conceived and carried out by international partnerships, an international forum for planning the future of astronomy will become increasingly valuable. In order that such a forum be effective, it will be necessary that it have the full support and participation of senior administrators within the agencies. From even modest beginnings, a foundation could be laid for more substantive cooperation and joint planning in the future and a context provided for interagency negotiations.

RECOMMENDATION: Approximately every 5 years the international science community should come together in a forum to share scientific directions and strategic plans, and to look for opportunities for further collaboration and cooperation, especially on large projects.

PUBLIC-PRIVATE PARTNERSHIPS

In addition to encouraging opportunities for international collaboration and partnership, the Astro2010 Committee also found opportunities within the United States for leveraging federal investments through partnering with privately funded research efforts in astronomy and astrophysics.

Ground-Based Optical and Infrared Astronomy

Most astronomical research in optical and infrared (OIR) astronomy was supported privately in the United States until 1958, when Kitt Peak National Observatory and AURA (Association of Universities for Research in Astronomy) were founded to provide public access to state-of-the-art OIR facilities. In subsequent years, competition between the private and public sectors dominated cooperation. However, the increasing cost of constructing large telescopes and, especially, the long-term cost of operating them, coupled with the desire of astronomers not affiliated with the institutions operating private telescopes to have access to those facilities, eventually led to the growth of public-private partnerships in the United States.

Today it is common to refer to the "OIR system," a concept envisioned by the 2001 decadal survey of astronomy and astrophysics, AANM, as the union of public and private OIR ground-based facilities that provide open telescope access to the U.S. astronomical community. On the basis of the NSF senior review, the National Optical Astronomy Observatory (NOAO) formed two committees to focus on the OIR system to ensure access for the astronomical community to a balance over all apertures. Priorities and recommendations for large telescopes were the purview of the Access to Large Telescopes for Astronomical Instruction and Research (ALTAIR) Committee. The Renewing Small Telescopes for Astronomical Research (ReSTAR) Committee achieves a similar goal with respect to smaller telescopes. The reports from ReSTAR and ALTAIR[4] provide a roadmap for producing upgraded instrumentation that enables U.S. observatories to maintain international competitiveness, they leverage the considerable private investment in these facilities, and they provide open-access observing time to the U.S. OIR community. Other important system activities include the enabling of OIR technology development, adaptive optics and interferometry, access to data archives for ground-based OIR telescopes, and training of future astronomers.

The NOAO and the international Gemini Observatory are operated via a cooperative agreement between NSF and a research management corporation, AURA. As summarized in Table 3.1, there are numerous ongoing partnerships for the existing U.S. ground-based OIR telescopes larger than 3 meters, including the majority of the largest-aperture (6.5- to 10-meter) OIR telescopes available to the U.S. community. The nature of these partnerships varies greatly, some consisting of universities partnering with NSF, or NASA, some between universities and foreign federal agencies, and others between private and state universities.[5]

The combination of publicly and privately funded facilities is a feature particular to the U.S. system internationally. Over this same 50-year period, Europe has taken a different path. With the founding of the European Southern Observatory (ESO) and its La Silla Observatory, Europe achieved near parity with the U.S. *public observatories* in the 1980s. The few other (non-ESO) OIR facilities in Europe still tend to be nationally funded, and there has been a gradual de-emphasis on institutionally operated observatories. Overall, the European model has evolved toward collective public investment in shared major facilities, major investments in new instruments and data systems, and high levels of user support. In the 1990s Europe achieved full parity with the *combined public-private* U.S. OIR system through the construction of the Paranal Observatory and its four 8-meter VLT telescopes. In some areas, such as high-resolution stellar spectroscopy, integral field spectroscopy, and data archiving, ESO has now established clear international leadership; the United States retains a lead in infrared detectors and high-contrast imaging.

Although the U.S. model is different from that in Europe and elsewhere, it offers some important advantages. Private institutions have attracted large sums of

[4] ReSTAR report, available at http://www.noao.edu/system/restar/files/ReSTAR_final_14jan08.pdf. Accessed May 2010. ALTAIR report, available at http://www.noao.edu/system/altair/. Accessed August 2010.

[5] The state university funding for astronomy is estimated to be 80 to 90 percent public money and 10 to 20 percent privately raised within the public university.

TABLE 3.1 Currently Operating OIR Facility Partnerships (>3-meter apertures only)

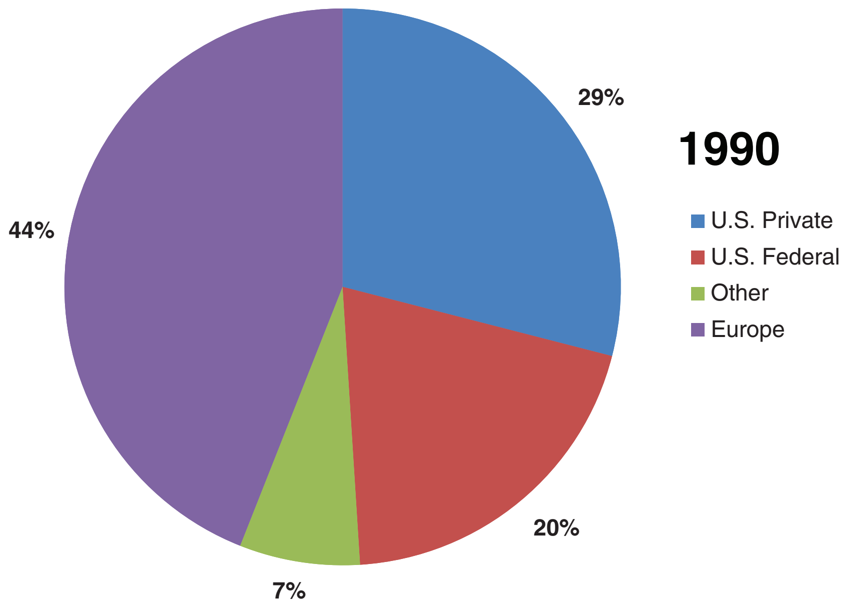
Observatory/Facility	Private Partners	Non-Federal/Public Partners	Federal/Public Partners
Apache Point Observatory	Astrophysical Research Consortium and private universities	Public universities	
Gemini Observatory		International partners	NSF through AURA
HET	Stanford University	University of Texas, Pennsylvania State University, Ludwig Maximilians Universität, and Georg August Universität	
IRTF			NASA and NSF through University of Hawaii
Keck Observatory	Caltech	University of California	NASA
KPNO 4 m and CTIO 4 m			NSF through AURA/NOAO
LBT Observatory	Research Corporation, University of Notre Dame	University of Arizona, Arizona State University, Northern Arizona University, Ohio State University, University of Minnesota, University of Virginia, and international partners (Germany and Italy)	
Magellan Observatory	Carnegie Observatories, Harvard University, MIT	University of Arizona, University of Michigan	
MMT Observatory		University of Arizona	Smithsonian
Palomar Observatory	Caltech	Cornell University	NASA/JPL, NOAO
SALT	American Museum of Natural History, Dartmouth College, Carnegie Mellon University	Rutgers University, University of Wisconsin, University of North Carolina, HET partners	
SOAR Telescope	Universities	Federal Republic of Brazil (MCT), University of North Carolina, Michigan State University	NOAO
WIYN Observatory	Yale University	University of Wisconsin, Indiana University	NOAO

private capital and philanthropy for telescope projects and thereby offered strong leveraging of available public funding, which has gone to support instrumentation in exchange for public access. It also has allowed scientists to carry out larger, bolder, and riskier investigations than those typically approved by national or international peer review panels for heavily oversubscribed public telescopes. The U.S. privately operated observatories have an operations model that is leaner than the Gemini Observatory and ESO's VLT, partially due to the provision of fewer user services. But access is restricted to the partner institutions, which may or may not include the federal government. The federally funded, publicly operated national observatories (NOAO and Gemini) provide merit-based access to OIR telescopes for the entire U.S. community and the sole access to large OIR telescopes for nearly half of U.S. astronomers, including students. Among the largest-aperture telescopes, Gemini provides 57 percent of the public-access nights; Keck, 25 percent (through the NASA partnership, with science restricted to that aligned with NASA's strategic goals); and TSIP participating telescopes (through NOAO time allocation), 18 percent of public access time.

These various public and private elements taken together allow the United States to remain scientifically competitive in OIR astronomy even though greater public resources are being invested overseas. However, the strengths in the OIR system are balanced by serious limitations that have become exacerbated over time and that serve to frustrate and polarize the U.S. OIR community. Several fundamental problems arise repeatedly. First is the financial gulf between the aspirations of the U.S. OIR community and the limited resources of NSF, a problem when considering even minor initiatives, but one that is especially acute when raising public funds for the next generation of large telescopes. Second is the competition for the limited NSF resources between the private observatories, which operate the lion's share of aperture for a subset of the user community, and the U.S. public observatories, which operate a small portion of the facilities with open access for all. A third problem is the competition between privately funded groups; although such competition has been generally beneficial to science historically, collaboration now seems imperative in order to realize next-generation facilities.

Figure 3.2 shows the effective ownership share in terms of the number of square meters of primary mirror of the world's largest optical-infrared telescopes and illustrates how the share has evolved over the last two decades. Four categories of owners are shown: U.S. private (blue), U.S. federal (red), Europe (purple), and other (green). The large decrease in the federal share during the era of 8-meter-class telescopes, from 1990 to today, is noteworthy. When one takes into consideration factors such as number of smaller telescopes the comparison becomes less stark, but by any measure the role of the U.S. public sector in this arena has been contracting *steadily*.

The corresponding breakdown in U.S. federal (NSF) funding is divided be-



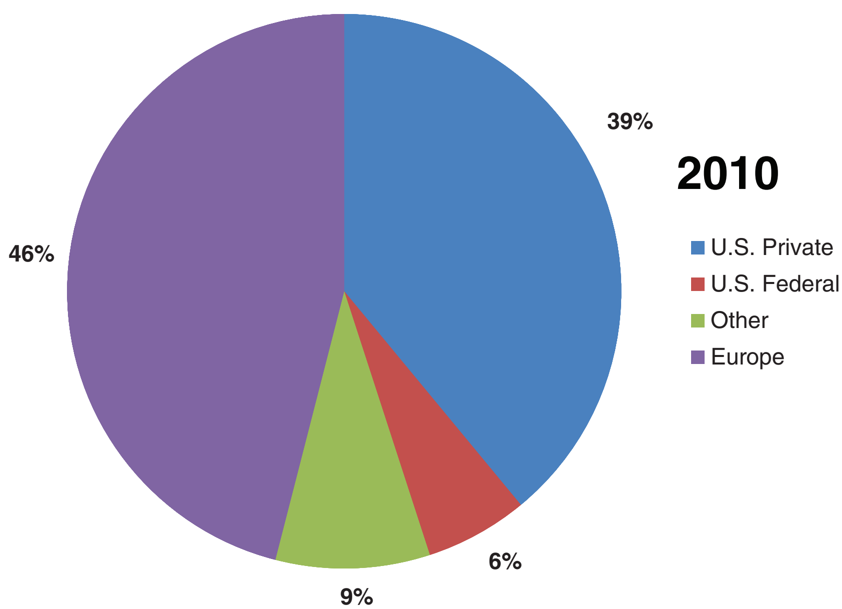


FIGURE 3.2 Distribution of optical and infrared telescope aperture around the world, 1990 and 2010. Colors denote the fraction of telescope primary mirror area held by U.S. private institutions (blue), U.S. federally funded national observatories (red), European-run observatories (purple), and other foreign-led observatories (green). The main change since 1990 has been a sharp decline in the share of telescope aperture available through U.S. public observatories.

tween support for public OIR observatories (NOAO and Gemini) at 81 percent, that for privately held telescopes through instrumentation programs (TSIP) at 14 percent, and design and planning for GSMT, LSST, and other future facilities at 5 percent. ATI and MRI funds allocated to OIR projects are not included in the calculation and are distributed across the pie, albeit unequally, but do not affect the main conclusion. Private observatories receive a small slice of the federal funding even though they comprise the majority of telescope aperture.

Ground-Based Radio, Millimeter, and Submillimeter Astronomy

Radio astronomy was a young and unestablished field when the National Radio Astronomy Observatory (NRAO) was founded in 1956. Unlike the situation in U.S. OIR astronomy, U.S. radio, millimeter, and submillimeter (RMS) astronomy has been primarily federally funded since its inception. However, just as in OIR astronomy, the increasing cost of constructing large RMS telescopes and, especially, the long-term cost of operating them, is now leading to growth of the idea of public-private partnerships.

Although the concept of an RMS system is not widespread, there are limited examples of public-private partnerships in radio astronomy (Table 3.2). NSF partners with universities through the University Radio Observatory (URO) program to operate, instrument, and provide public access to unique radio observatories, currently the Caltech Submillimeter Observatory (CSO), the Combined Array for Research in Millimeter-wave Astronomy (CARMA), and a small amount for the Allen Telescope Array (ATA). The URO program is responsible for training at the student and postdoctoral level many of today's prominent RMS astronomers as well as the highly skilled technical staff who are needed to build and operate the state-of-the-art receivers and instruments.

NRAO is operated via a cooperative agreement between NSF and a not-for-profit research management corporation, AUI (Associated Universities, Inc.). Its facilities can lay legitimate claim to international leadership in their capabilities, at least for now. The complementary scientific capabilities provided by the national observatory (now including ALMA), the smaller university-operated facilities, and more targeted investments in experiments (e.g., CMB and the epoch of reionization) and technology development should allow the United States to maintain its position of international leadership in radio astronomy for at least another decade. However, significant investments in next-generation facilities by Europe, China, Australia, and South Africa (~$100 million each) are beginning to challenge this leadership.

Currently, the balance of NSF-AST support for RMS activities is approximately 60 to 65 percent for NRAO plus ALMA telescope operations, 15 to 20 percent for university-operated radio observatories, 5 to 10 percent for experiments, and

TABLE 3.2 Currently Operating RMS Facility Partnerships

Observatory/ Facility	Private Partners	Non-Federal/Public Partners	Federal/Public Partners
ALMA		International partners	NSF through AUI
Arecibo			NSF (AST and AGS) and NASA through Cornell University/NAIC
ARO		University of Arizona and international universities	
ATA	SETI Institute	UC Berkeley	
CARMA	Caltech, University of Chicago	UC Berkeley, University of Illinois, University of Maryland	NSF
CSO	Caltech	University of Texas	NSF
EVLA, VLBA, GBT		EVLA's international partners	NSF through AUI/NRAO
LMT		University of Massachusetts and Mexico	
SMA		Taiwan	Smithsonian
SPT	University of Chicago, Case Western Reserve University	UC Berkeley, UC Davis, University of Illinois, University of Colorado, and international universities	NSF-OPP, Smithsonian

10 percent for technology and future facilities development. The fraction allocated to NRAO plus ALMA will increase when ALMA becomes fully operational in 2014.

PARTNERSHIP OPPORTUNITIES

Many of the papers provided by the community as input to Astro2010 described projects that involve significant partnership—between university groups, between non-federal and federal partners, between federal agencies, and involving international collaborations. Almost all of the proposed large-scale projects ranked most highly by the Astro2010 Program Prioritization Panels involve a significant international collaboration of one form or another. The committee notes in particular LISA (NASA plus ESA) and participation in an international Atmospheric Čerenkov Telescope Array, from the Panel on Particle Astrophysics and Gravitation; WFIRST and IXO (NASA plus ESA), from the Panel on Electromagnetic Observations from Space; CCAT (a U.S.-led project with international university partners) and HERA-II (a U.S.-led project but a pathfinder for the international HERA-III project, aka Square Kilometer Aray (SKA)-low in the post-2020 timeframe), from the Panel on Radio, Millimeter, and Submillimeter Astronomy from the Ground, which recommended a continuing U.S. role in the development of concepts for the international SKA-mid and SKA-high components; and GSMT (in either version, a privately led project in the United States with significant or perhaps eventually even dominant international participation) and LSST (proposed as a private-public partnership), from the Panel on Optical and Infrared Astronomy from the Ground. Complex equipment is essential for progress in addressing the compelling science opportunities outlined in Chapter 2.

CONCLUSION: Complex and high-cost facilities are essential to major progress in astronomy and astrophysics and typically involve collaboration of multiple nations and/or collaboration of federal and non-federal institutions. These partnerships bring great opportunities for pooling resources and expertise to fulfill scientific goals that are beyond the reach of any single country. However, they also present management challenges and require a new level of strategic planning to bring them to fruition.

OIR and RMS on the Ground

The 14-nation ESO consortium is on track to become the undisputed leader in ground-based OIR astronomy with its planned construction of the 42-meter European Extremely Large Telescope (E-ELT) facility by 2018 and to play a more prominent role in RMS by investing significantly in the SKA. By concentrating most of its resources into a single international partnership, Europe has minimized duplication of capability between facilities, created a major international research center, and established a funding line for construction that is intended to lead from ALMA to E-ELT to SKA. As a large monolithic, multinational institution, ESO inevitably carries a larger overhead than a U.S. private observatory, but it serves as a good example of a successful international partnership.

Optical and Infrared

The United States, in contrast to Europe, is relying on an extension of its private-public model to remain competitive in the era of ELTs. The two major GSMT projects aiming to construct 30-meter-class telescopes, the Thirty Meter Telescope (TMT) and Giant Magellan Telescope (GMT), are organized by private and public U.S. universities and other non-profit institutions. It is notable that many countries around the world (Australia, Canada, China, India, Japan, and Korea) are forming public-private partnerships with these U.S. groups. Although GSMT was endorsed by the 2001 AANM report, U.S. public participation in either of these projects has yet to be determined.

In Chapters 6 and 7, the committee recommends public participation by the United States in at least one of the GSMT projects, participation that could come in the form of contributions to construction, operations, and/or advanced instrumentation. This would leverage the large private contribution, maintain a leading U.S. role in OIR astronomy, and realize the scientific potential of a 30-meter-class optical-infrared telescope for U.S. astronomers. The benefits of such participation could go beyond making a fraction of the observing time available to the entire community of U.S. astronomers. With a sufficiently early commitment from NSF, the broad U.S. community would have input into GSMT governance and could play an important role in ensuring that the telescope and its instruments will meet the needs of the full U.S. community of users and enhance the development and use of this facility by engaging the enthusiasm and experience of the entire community. This includes NOAO, which presumably would be identified as the public partner, with responsibility for representing the public interests during both the construction and the operation phases.

Rather than view Astro2010's prioritization as a competition between LSST and GSMT, the Program Prioritization Panel on Optical and Infrared Astronomy from the Ground in its report stresses the synergy of these two projects. Each would be greatly enhanced by the existence of the other, and the omission of either would be a significant loss of scientific capability. The combination of wide-area photometric surveys and large-aperture spectroscopy has a long, productive history in OIR astronomy: interesting sources identified in the wide-field survey are studied in detail with the larger telescope. The panel concluded that a crucial goal for ground-based OIR astronomy in the coming decade should be to realize the potential of the combination of these facilities, as linchpins for an enlarged and more capable U.S. ground-based OIR system. Furthermore, the synergies with U.S.-led space missions are significant.

Radio, Millimeter, and Submillimeter

The next generation of radio telescopes beyond ALMA will exploit phased-array technology and a new generation of fast digital correlators to make possible radio telescope arrays with thousands of linked antennas, with collecting areas approaching a square kilometer, and extending up to thousands of kilometers. Retrofitting existing telescopes with focal plane arrays will enable (and already has enabled) gains of orders of magnitude in mapping speed. The most ambitious of these projects, the SKA, was co-ranked as the highest-priority large facility (with the E-ELT) for the coming decade in the European ASTRONET decadal survey,[6] and it has strong additional support from Australia and South Africa, the candidate sites for the SKA.

The SKA project encompasses the development of the next-generation radio capability to operate in the meter-to-centimeter wavelength range. SKA technology development was a key part of the RMS program endorsed by the AANM report; significant NSF funding ($12 million) became available only in 2007. As noted in the report of the AUI Committee on the Future of U.S. Radio Astronomy[7] and as defined in the report of the Astro2010 Panel on Radio, Millimeter, and Submillimeter Astronomy from the Ground, the SKA concept is likely to be fulfilled by separate facilities delivering huge increases in collecting area via different technical approaches appropriate to three separate wavelength ranges, referred to as SKA-low (1- to 3-meter wavelength), SKA-mid (3- to 100-centimeter wavelength), and SKA-high (0.6- to 3.0-centimeter wavelength). Concept and technology development for the SKA is being undertaken by the international SKA consortium, which includes some 55 institutions in 19 countries. Many of the areas of technology development recommended in the RMS report are crucial steps along the road to achievement of the SKA.

The dramatic increase in scientific capability promised by SKA is directly reflected in the scope, complexity, and technical challenge of SKA concept development. At the present time, the detailed path to construction of any of the three SKA facilities is not clear. However, continued steady development of technology will lead to the next generation of radio facilities.

The HERA program, a project that was highly ranked by the RMS-PPP and included by the committee in its list of compelling cases for a competed mid-scale program at NSF, provides a development pathway for the SKA-low facility. Progress on development of the SKA-mid pathfinder instruments—the Allen Telescope Array in the United States, the MeerKAT in South Africa, and the ASKAP in Australia—and in new instruments and new observing modes on the existing facilities operated by NRAO and the National Astronomy and Ionosphere Center will provide crucial insight into the optimal path toward a full SKA-mid. It is natural for the United States to build on its long, successful heritage with the EVLA, GBT, and VLBA in further developing the capabilities leading toward the SKA-high. It is primarily through technology development that the United States can remain an active partner in the concept development of the next-generation meter-to-centimeter wavelength radio facilities through the international SKA collaboration.

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[6] ASTRONET, *The ASTRONET Infrastructure Roadmap, Draft Report*, May 5, 2008, available at http://www.astronet-eu.org/IMG/pdf/Astronet_Infrastructure_Roadmap.pdf.

[7] Associated Universities, Inc., *Future Prospects for U.S. Radio, Millimeter, and Submillimeter Astronomy: Report of the Committee on the Future of U.S. Radio Astronomy,* revised February 2009, available at http://www.aui.edu/pr.php?id=20081003.

Particle Astrophysics and Gravitation

Design efforts in the United States and in Europe for the next-generation TeV Čerenkov telescope, AGIS and CTA, respectively, are underway and follow a recent worldwide explosion of activity in gamma-ray astrophysics, with the U.S.-led Fermi Gamma-ray Space Telescope (FGST) in space and a host of TeV Čerenkov telescopes on the ground (VERITAS, HESS, MAGIC, Milagro, CANGAROO, and HEGRA). The proposed new instruments would increase sensitivity and field of view by an order of magnitude. Because the two designs have similarities and complementarity (including the location of VERITAS and HESS in different hemispheres), opportunities for collaboration exist and discussions are underway. This is yet another example in which common scientific interests, current capability, and design complementarity make collaboration not only a means of reducing cost to each partner, but also a way of creating a more capable observatory.

Space Observatories

The Laser Interferometer Space Antenna (LISA) and the International X-ray Observatory (IXO) are two transformational missions where the convergence of scientific goals, complementarity of expertise, and the desire to produce more science per dollar has made partnering essential. LISA is a relatively mature NASA/ESA collaboration, while IXO is the result of a more recent merger of the U.S. Con-X and the ESA XEUS missions, with JAXA as an additional partner. NASA will consider Astro2010 advice on the relative rankings of LISA and IXO, and in Europe the two are competing for the first L(arge)-class launch slot (scheduled for 2020) against the Europa Jupiter System Mission (EJSM) (an outer planets mission) in the ESA Cosmic Vision program, whose down-select process is beginning in 2010. From the U.S. perspective, the committee would like to see both LISA and IXO go forward, and an implementation plan for NASA is given in Chapter 7. ESA, on the other hand, may choose a different prioritization, or choose to go with EJSM.

Even more complex is the potential partnering between NASA, DOE, and ESA on a dark energy mission. Because of the common interests in the science of dark energy, as well as complementary technical capabilities, NASA and DOE have been planning for the Joint Dark Energy Mission (JDEM) since 2003. Euclid is a European mission concept aimed at cosmology and dark energy, which is competing for one of two M(edium)-class launch slots, with a decision expected in late 2011 and launches scheduled for 2018 and 2019. The overlap in goals and scope between the proposed U.S. and European missions is significant, and there is potentially a grand partnering arrangement involving NASA, DOE, and ESA if the expanded scientific priorities set by Astro2010 for such a mission can be aligned among the partners, and assuming that the arrangement is consistent with the United States playing a clear leadership role. However, reconciling the outcome and timing of three different decision-making processes is a challenge.

AGENCY PARTNERSHIPS AND INTERFACES

Revolutionary discoveries in astronomy over the past two decades have broadened the field and created new interfaces with other areas of science—particle physics (the birth and early evolution of the universe, cosmic rays, dark matter, and dark energy), nuclear physics (the origin of the chemical elements and neutron star structure), gravitational physics (black holes and gravitational waves), planetary science (the solar system and exoplanets), computer science (analysis of large data sets), and soon biology (life in the universe). Today, astronomical research involves not only astronomers, but also scientists from many other fields, especially physics. Thus there are more funding agencies involved, which necessitates careful handling of the complex interfaces between them.

Currently the NASA Astrophysics Division budget within the Science Mission Directorate is roughly $1.1 billion per year (including construction of major facilities); NSF-AST within the Directorate for Mathematical and Physical Sciences (MPS) is $250 million per year. Funding from NSF-OPP and NSF-PHY is about $10 million and $20 million, respectively, with an additional $30 million per year going to operations for the Advanced LIGO. DOE OHEP within the Office of Science funds particle astrophysics at a level of about $100 million per year. Whereas NSF-AST funds investigator-driven research broadly in the astrophysical sciences and NASA's Astrophysics Division funds space-mission-driven astrophysics research broadly defined, the interests of DOE's OHEP and NSF-PHY and NSF-OPP are more focused. With so many agencies involved, coordination is critical to obtaining optimal value, in terms of both scientific return and cost-effectiveness. Understanding the different missions and cultures of the funding agencies is a prerequisite to optimizing investment.

- *DOE Office of High Energy Physics.* DOE is a mission agency, and OHEP's mission is to seek a fundamental understanding of matter, energy, space, and time, which resonates strongly with much of the research at the frontier of astrophysics. The bulk of the program consists of the construction and operation of high-energy particle accelerators and the support of the scientists who use them. OHEP's interest in particle astrophysics has been spurred by the recognition that dark matter is likely to be a new form of matter, that dark energy may be a new fundamental field, and that the universe may well be the best laboratory for making progress in testing ideas about the unification of the forces and particles of nature. The recent report[8] of the Particle Astrophysics Scientific Assessment Group (PASAG) to the High Energy Physics Advisory Panel (HEPAP), which advises DOE and NSF, defined priorities for high-energy physics funding of astrophysics projects. Three broad criteria were laid out: (1) importance of the science and discovery potential consistent with the fundamental physics mission of OHEP; (2) necessity of OHEP expertise and/or technology to enable important projects and to make unique, high-impact contributions (e.g., silicon detectors and electronics on the Fermi Gamma-ray Space Telescope, or data acquisition and processing on the Sloan Digital Sky Survey, or CMB research); and (3) programmatic issues of balance and the international context. PASAG recommended that these criteria be used, in descending order of importance, to prioritize the large number of opportunities in astrophysical research to be funded.

- *NSF Physics Division and Office of Polar Programs.* NSF-PHY funds investigator-driven research across all areas of physics, including nuclear, particle, atomic, biological, gravitational, plasma, and theoretical physics. Nuclear and particle astrophysics science falls within the NSF-PHY portfolio, and there is a specific program for it. NSF-OPP is the steward for U.S. science in Antarctica, and it funds (or co-funds) a variety of astrophysics projects at the South Pole (e.g., CMB experiments, the IceCube neutrino detector, and the 10-meter South Pole Telescope). Through the MREFC process, NSF-PHY has made a large investment in the construction and operation of the LIGO facility, and, in this decade, the Advanced LIGO detectors.
- *NSF Atmospheric and Geospace Sciences Division.* NSF-AGS (formerly NSF-ATM) is part of the Geosciences (GEO) Directorate and provides the bulk of the grant funding for solar scientists. Additionally, for solar astronomy NSF-AGS supports the High Altitude Observatory of the National Center for Atmospheric Research. NSF-AGS is concerned mostly with the effects of the Sun on our terrestrial environment, whereas NSF-AST, which supports solar astronomy through operation of NSO, views the Sun as a star that can be studied in great detail due to its unusual proximity.

Currently there are a number of areas of astrophysical research where the interests of more than one of these agencies converge. The synergies and complementarity between the agency capabilities are important. As examples, instruments developed on NSF-funded ground- and balloon-based instruments have been flown by NASA in space (on WMAP and now on Planck). NASA's long-duration balloon program depends on the support of NSF's McMurdo station in Antarctica,

[8] U.S. Department of Energy, *Report of the HEPAP Particle Astrophysics Scientific Assessment Group (PASAG)*, October 23, 2009, available at http://www.er.doe.gov/hep/panels/reports/hepap_reports.html.

and NASA satellites and downlink stations are critical for communication and transfer of astronomical data from NSF's South Pole research station. NSF radio observatories are used for the telemetry of spacecraft data. DOE physicists were essential for the successful design, construction, and operation of the Large Area Telescope on FGST, and the Dark Energy Camera is receiving both DOE and NSF funding and will be a facility instrument on an NSF-supported telescope. Scientists from all three agencies contribute special expertise in detector fabrication and data acquisition to many successful partnerships. Although funding by multiple agencies adds complexity, it also adds significant value. Each of the agencies brings special technical strengths and experts as well as unique research communities. Provided that the efforts of the different agencies are effectively coordinated, there are significant benefits to science and to the nation in collaboration, as has been demonstrated in many successful joint ventures.

Coordination between the agencies is facilitated by a variety of mechanisms and currently takes place at several levels. The agencies have program managers who meet both formally and informally to coordinate at the agency level, sometimes facilitated by OSTP. In addition, a number of standing FACA advisory committees provide expert community advice. These include the High Energy Physics Advisory Panel, for the DOE's OHEP and NSF-PHY; the Mathematical and Physical Sciences Advisory Committee (MPSAC), for NSF-AST and NSF-PHY; the Astrophysics Subcommittee of the NASA Advisory Council's Science Committee, for the NASA Astrophysics Division; and the Astronomy and Astrophysics Advisory Committee (AAAC), which advises NSF, NASA, and DOE. All of these FACA committees can effectively provide, and have provided, the agencies with advice on issues requiring rapid action. Some of the advice is agency specific, with one FACA committee reporting to one agency. Some of the advice crosses agency boundaries and requires the formation of an ad hoc task force.

While all of these committees play valuable roles, modifications to the advisory structure could improve the coordination between the agencies and in many instances improve the effectiveness of agency-specific advice. Over the past 10 years the advisory structure at NASA has been reorganized several times. The most recent reorganization of the NASA Advisory Council and its subcommittees appears to have effectively addressed the issue of shortening the conduit between the advisory body and the science managers for whom the advice is intended (as recommended by the NRC's NAPA report[9]). NSF-PHY and NSF-AST receive only informal input from MPSAC, an advisory committee to NSF's entire Directorate for Mathematical and Physical Sciences whose effectiveness could be improved. While MPSAC facilitates cross-division strategic coordination, NSF-AST will continue to need tactical

[9] National Research Council, *A Performance Assessment of NASA's Astrophysics Program,* The National Academies Press, Washington, D.C., 2007.

advice from the community, which it currently receives through its Committee of Visitors and senior review processes. The survey committee urges MPS to find mechanisms to provide NSF-AST with a more robust means of expert community input. Finally, the charges to the NRC Committee on Astronomy and Astrophysics and the AAAC have evolved over the past decade to the point of considerable overlap, which is addressed separately below.

INTERAGENCY TACTICAL ADVICE

The AAAC was created by Congress in 2002 to advise Congress, OSTP, NASA, and NSF (and also, by an amendment in 2005, DOE) on matters of interagency coordination as well as on the health of the astronomical enterprise generally. Because many of the critical elements of the core research program (described in Chapter 5) within this national enterprise cut across agency boundaries, optimizing the program as a whole requires looking across agencies. The AAAC can play a key role in providing continuing advice to DOE, NASA, and NSF on funding across the three agencies in the areas of:

- Support of individual and group grants funding, including the balance between grants programs, mission/facility operations, and the design and development of new missions/facilities;
- Overall support of theoretical and computational astrophysics;
- Data archiving and dissemination, and funding for data analysis software, including the optimal infrastructure for the curation of archival space- and ground-based data from federally supported missions/facilities;
- Laboratory astrophysics; and
- Technology development.

Last but not least, the AAAC can be tasked to provide timely, ad hoc advice on pressing cross-agency matters; it has in the past provided essential white papers on exoplanets, dark energy, and CMB polarization using a task force approach.

STEWARDSHIP OF THE DECADAL SURVEY

The decadal survey is a strategic document built on 2 years of work involving a significant fraction of the community. The strategy laid out is based on the best information available at the time on scientific, technical, and fiscal issues, using reasonable assumptions about the future. However, astronomy is a highly progressive activity, and important scientific discoveries, technical advances, and changes in budgets and international plans will require revisiting parts of the strategy over the next decade. Moreover, this report identifies in Chapter 7 a number of decision points at which the need for critical expert community input can already be anticipated. It also is likely that a mid-decade review of progress and of issues related to international standing and partnerships—to generate recommendations for possible mid-course corrections—would be valuable. The committee believes that the existing standing agency and interagency committees—including the AAAC—are not well suited or constituted to provide the necessary strategic advice, given that they were constituted primarily to give rapid feedback on tactical matters brought to them by the agencies. This important function should remain their province.

The survey committee believes that there will be a continuing need for regular assessments of the progress made toward the implementation of the Astro2010 proposed program, and a need for a mid-decade assessment that would include an analysis of whether any of the contingencies described in this report have been encountered and make recommendations for appropriate action as discussed below.

> **RECOMMENDATION: NASA, NSF, and DOE should on a regular basis request advice from an independent standing committee constituted to monitor progress toward reaching the goals recommended in the 2010 decadal survey of astronomy and astrophysics, and to provide strategic advice to the agencies over the decade of implementation. Such a decadal survey implementation advisory committee (DSIAC) should be charged to produce annual reports to the agencies, the Office of Management and Budget, and the Office of Science and Technology Policy, as well as a mid-decade review of the progress made. The implementation advisory committee should be independent of the agencies and the agency advisory committees in its membership, management, and operation.**

The survey committee believes that the role of a decadal survey implementation advisory committee will be all the more critical in the decade to come, in part because of the technical decision points that have been flagged, in part because of the many partnerships (agency, public/private, and international) that are involved with most of the highly ranked projects, and in part because of potentially rapid changes in the scientific landscape (particularly in the exoplanet and CMB fields). The role of international partners in particular, with their own priorities, agency priorities, and decision processes, demands a more agile and adaptive follow-through on the Astro2010 decadal recommendations than can be accommodated by a 10-year review cycle.

4

Astronomy in Society

Astronomy offers a high return on investment for the United States, attracting young people to science and technology careers and providing the kind of education and training that can help solve major societal challenges involving science and technology. Because astronomy enjoys broad public appeal as an accessible science, it also plays a role in K-12 science, technology, engineering, and mathematics (STEM) education[1] and encourages science literacy in the population as a whole. Many of the breakthroughs being made in our understanding of the universe involve close connections with other scientific fields, developments in which also find increasing application in our everyday lives. At the same time, an enthusiastic and vibrant amateur community continues to play an important role in the advancement of the field in specific areas (e.g., variable stars; discovery of comets, supernovae, and microlensing events) (see Figure 4.1).

Practitioners of astronomy and astrophysics pursue research in the United States in a wide variety of venues, including public and private universities and observatories; national observatories, centers, and laboratories; industry; and museums and planetariums. There is a recognized need to encourage underrepresented groups to participate in the profession. Recent growth in the number of Ph.D. astronomers

[1] Education in STEM as important areas of competency is emphasized in, for example, the America COMPETES Act (H.R. 2272), initiatives within the U.S. Department of Education and National Science Foundation, and in *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* a report of the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine (The National Academies Press, Washington, D.C., 2007).

FIGURE 4.1 In 2008, 14-year-old Caroline Moore became the youngest amateur astronomer to discover a supernova, SN2008ha in the constellation Pegasus. She was a featured guest of President Obama at the October 2009 White House Star Party. SOURCE: Robert E. Moore, Deer Pond Observatory.

has been driven by the exciting opportunities in the field. Although the research enterprise itself may not be able to offer permanent positions to all qualified new entrants to the field, training in U.S. astronomy and astrophysics programs affords the ability to pursue many valuable career paths.

BENEFITS OF ASTRONOMY TO THE NATION

Astronomy Engages the Public in Science

Astronomy stirs the public imagination and the human spirit. Indeed, the results of modern astronomical research are already deeply ingrained in our culture, and terms like "light-year," "big bang," and "black hole" have joined the vernacular. The astronomy aisle of any fully stocked bookstore includes large, beautiful picture books of the cosmos as well as technical books about the advancing frontier—written by working astronomers, writers educated as astronomers, and journalists. About once per week on average, national television broadcasts an interview with a professional astronomer, a rate that increases dramatically during the semiannual meetings of the American Astronomical Society (AAS). The steady stream of discoveries from space missions and ground-based telescopes generates hundreds of press stories per year and has made some facilities, such as the Hubble Space Telescope (HST), into international icons.

A single astronomical image can play a large role in our cultural life. The Eagle Nebula, framed by HST, is an inspiring work of art (Figure 4.2). The iconic Apollo 8 photograph of Earth rising over the lunar landscape, showing its blue oceans, dry land, and clouds floating alone in the cosmic void with no national boundaries visible (Figure 4.3), testifies to the unity of mankind far more effectively than any political speech—and in delivering that message emphasizes a value to society that may be beyond measure.

Astronomy on television has come a long way since the 1980 PBS premier of Carl Sagan's ground-breaking multipart documentary *Cosmos*. Many cable channels offer copious programming on a large variety of astronomical topics, and the big-three networks occasionally offer specials on the universe, too. Another barometer of the public's curiosity about the cosmos is the popularity of IMAX-format films on space science, as well as the number of big-budget Hollywood movies whose plotlines derive directly or indirectly from space themes (including 5 of the top 10 grossing movies of all time in the United States). The Internet also plays a pervasive role in bringing astronomy to the public, attracting worldwide audiences on websites such as Galaxy Zoo (http://www.galaxyzoo.org) and others that feature astronomical events such as NASA missions. Astronomy applications are now available for most mobile devices, and even social networking technology plays a role, e.g., by enabling tweets from the Spitzer NASA Infrared Processing and Analysis Center (http://twitter.com/cool_cosmos).

Public interest in astronomy has caught the attention of corporate giants as well, which see commercial value in and synergy with what astronomers do. The Microsoft World Wide Telescope, a corporate version of previously underfunded efforts of astronomers to coordinate the world's public-domain cosmic imagery and make it available in one resource, allows people on home PCs to explore the cosmos as if they were at the helm of the finest ground- and space-based telescopes. And Google's interest in maps now extends to the universe, as seen in Google Earth, Google Sky, Google Moon, and Google Mars. These nascent corporate efforts to connect people with the broader universe offer yet another indication of the breadth and depth of influence that discovery of the cosmos enjoys in our culture.

Astronomers, too, have seized opportunities to be innovators in public outreach. New approaches to promoting public engagement in science include "citizen science," bringing astronomy to wide audiences via large databases available on the Internet and enabling amateur scientists to participate actively in the analysis of astronomical data[2] (Figure 4.4). The continued growth of astronomical data sets will allow further opportunities for public involvement over the coming decade.

[2] Galaxy Zoo is one project that enables online users to classify galaxies from Sloan Digital Sky Survey images; to date more than 230,000 registered users have analyzed data, and a few have produced unique new discoveries (see Figure 4.4). The success of Galaxy Zoo has inspired the creation

FIGURE 4.2 The dust sculptures of the Eagle Nebula are evaporating as powerful starlight whittles away these cool cosmic mountains, leaving statuesque pillars. SOURCE: The Hubble Heritage Team (STScI/AURA), ESA, NASA.

FIGURE 4.3 Earthrise from the Moon, as seen by the Apollo 8 crew. SOURCE: NASA.

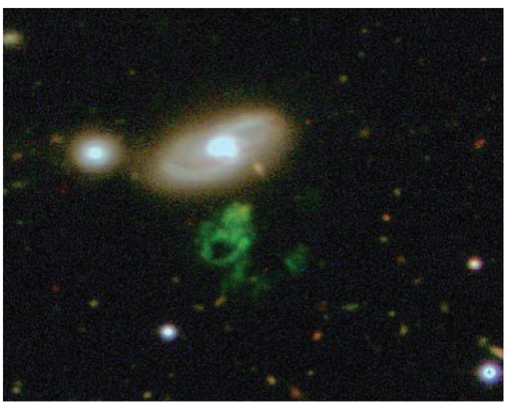

FIGURE 4.4 Image of a new large and diffuse extragalactic object, Voorwerp, which is thought to be a gas cloud illuminated by a nearby active galactic nucleus discovered by Galaxy Zoo citizen scientist Hanny van Arkel. SOURCE: Dan Smith (Liverpool John Moores) and Peter Herbert (University of Hertfordshire). Image obtained using the Isaac Newton Telescope, Roque de los Muchachos, La Palma.

FIGURE 4.5 President Barack Obama and First Lady Michelle Obama take part in the "star party" on the White House lawn in October 2009. SOURCE: Tim Sloan/AFP/Getty Images.

The recently concluded International Year of Astronomy (IYA) 2009, initiated by the International Astronomical Union and UNESCO, and endorsed by the United Nations and the U.S. Congress, was a global effort involving nearly 150 countries participating in astronomy activities on all scales, from local to international. The U.S. effort involved tens of thousands of people. The year-long enterprise had several focus projects, including the production and distribution of well over 100,000 telescopes designed to reproduce the seeing power that Galileo had when he first turned his telescope skyward;[3] more than 1,000 public observing events in 70 countries; and the generation of special IYA websites by NASA and similar international organizations. The U.S. effort culminated on October 7, 2009, when President Obama hosted a star party for local school children on the White House lawn (Figure 4.5).

of similar citizen science projects to analyze imaging from space missions to the Moon and Mars, and the model is being duplicated in other fields of science.

[3] These telescopes are known as Galileoscopes; 110,000 were produced and delivered in 2009, and 70,000 more were ordered for delivery scheduled in the first quarter of 2010.

The federal government provides significant support for many of these informal education and outreach activities. For 15 years, NASA has devoted roughly 1 percent of the cost of major missions to education and public outreach and has created imaginative websites and activities involving the use of astronomical data for students, teachers, and the public. NSF supports astronomy education and public outreach through budget allocations at its observatories and technology centers, as well as through its Directorate for Education and Human Resources and specific grants programs, especially those for young people such as the CAREER and astronomy and astrophysics postdoctoral fellow awards. NSF Astronomy Division data indicate that more than 6 percent of research grant funding is devoted to education and special activities.

The funding for education and public outreach by NASA increased dramatically from 1996 to 2004 but has leveled off in the past half decade (Figure 4.6). For an even better return on the federal investment in education and public outreach, a more rigorous program of assessment is needed of outcomes and efficacy across

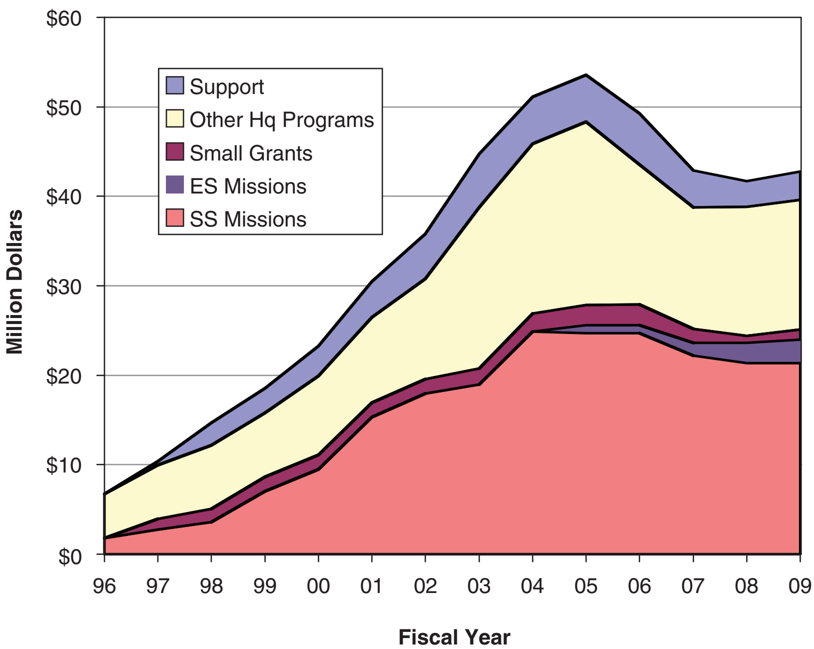

FIGURE 4.6 Total budget for NASA Earth and space science education and public outreach from 1996 to 2009. The numbers include support for all NASA education and public outreach activities, including astronomy, Earth sciences, space science, and other disciplines. NOTE: Support, directorate personnel support and other support costs; ES, Earth sciences; SS, space sciences. SOURCE: NASA Science Mission Directorate.

the entire spectrum of astronomical education and public outreach activities,[4] especially the many less formal outreach activities.[5] The committee believes that NASA's important investments in informal education and public outreach at the current level of 1 percent of each mission's cost should be continued.

Engagement with Astronomy Improves Science Literacy and Proficiency

As has been documented in several recent high-profile reports,[6] the United States is ill-prepared for the economic and technical challenges of the 21st century. In particular, there is an urgent need to develop knowledge-based resources throughout society and to increase the number of teachers and students in STEM disciplines. For example, Jon Miller, in his paper entitled "Civic Scientific Literacy across the Life Cycle," states that only 30 percent of the U.S. population is scientifically literate.[7] Furthermore, the National Science Board estimates that more than a third of Americans do not understand that Earth orbits the Sun and that two-thirds are unaware of the big bang origin of the universe;[8] and a study performed by the California Academy of the Sciences found that nearly half of American adults do not know the approximate percentage of Earth's surface that is covered with water and that fewer than 1 percent know what fraction of that water is fresh.[9] National science tests administered to schoolchildren show proficiency in science dropping from 33 percent in grades 4 through 8 to only 18 percent by grade 12.[10] For the United States to remain scientifically and technologically competitive, science literacy and proficiency must become an urgent national priority.[11]

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[4] National Research Council, *NASA's Elementary and Secondary Education Program: Review and Critique,* The National Academies Press, Washington, D.C., 2008.

[5] As highlighted in National Research Council, *Learning Science in Informal Environments: People, Places, and Pursuits* (P. Bell, B. Lewenstein, A.W. Shouse, and M.A. Feder, eds.), The National Academies Press, Washington, D.C., 2009.

[6] See, e.g., NAS, NAE, IOM, *Rising Above the Gathering Storm,* 2007, at http://www.nap.edu/catalog.php?record_id=11463; and Norman Augustine, *Is America Falling Off the Flat Earth?* 2007, at http://books.nap.edu/openbook.php?record_id=12021.

[7] Jon D. Miller, "Civic Scientific Literacy across the Life Cycle," a paper presented at the annual meeting of the American Association for the Advancement of Science, San Francisco, California, February 17, 2007.

[8] National Science Board, *Science and Engineering Indicators 2006,* National Science Foundation, Arlington, Va., available at http://www.nsf.gov/statistics/seind06/pdf/volume1.pdf.

[9] See California Academy of Sciences, "American Adults Flunk Basic Science: National Survey Shows Only One-in-Five Adults Can Answer Three Science Questions Correctly," press release, 2009, available at http://www.calacademy.org/newsroom/releases/2009/scientific_literacy.php.

[10] National Center for Education Statistics, *The Nation's Report Card: Science 2000,* NCES 2003-453, U.S. Department of Education, Washington, D.C., 2003.

[11] NAS, NAE, IOM, *Rising Above the Gathering Storm,* 2007.

Addressing the current deficiencies will require that teachers be engaged to improve the science attainment of U.S. students and also that research scientists find new ways to make the science enterprise more accessible and inviting to young people. Because of its broad public appeal and its many ties to other branches of science and technology, astronomy can contribute in uniquely powerful ways. Public interest in astronomy translates to opportunities to educate and influence future scientists, engineers, teachers, policy makers, and the public at large, through informal education or formally, in the classroom. Also relevant to enhancing understanding of science are the connections that astrophysical research has today with many other areas of STEM: geology (planets), aerospace engineering (space missions), biology (the search for life in the cosmos), chemistry (molecules in the interstellar medium), high-performance computing (data management and computational astrophysics), mechanical engineering (innovative design of telescopes and observatories), electrical engineering and advanced optics (sensor physics and adaptive optics), computer science (massive data sets and analysis), nuclear physics (matter at ultra-high density), particle physics (the study of the big bang and cosmic origins, dark matter), and even medicine (many of the most sensitive and therefore least invasive cameras for examining the body contain detectors originally developed for astronomy, and adaptive optics tools for high-resolution imaging developed for astronomy are now being applied to ultra-precise imaging of the living human retina).

Astronomy Inspires in the Classroom and Beyond

The engagement of astronomers in education at the K-12 and college levels is considerable. Undergraduate astronomy courses in colleges and universities serve 250,000 students annually, representing about 10 percent of all undergraduates nationwide. Among them are about 15 percent of future K-12 teachers, for whom introductory astronomy is often their only science course.[12]

Astronomy education itself is now recognized as an important area of research, and education specialists (Ph.D.-holding astronomers with additional education degrees and credentials) are being hired in major research university departments, as well as in smaller teaching-oriented college physics and astronomy departments, to develop and test new approaches to teaching that break down conceptual barriers to understanding. A result of this focus on learning has been a steady increase in interactive teaching, which produces measurable learning gains over traditional lecture course formats.

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[12] American Institute of Physics, *Roster of Astronomy Departments with Enrollment and Degree Data,* AIP R-395.14, American Institute of Physics, College Park, Md., 2007; see also analogous reports from 1998 to 2006.

The emergence of astronomy education during the past decade has precipitated establishment of the *Astronomy Education Review* (http://aer.aip.org), which produces peer-reviewed articles on education research. In addition, the Astronomical Society of the Pacific and the AAS have played increasing roles in bringing together education specialists and college teachers alike.

At the precollege level, exposure to astronomy is largely through informal education and public outreach. Ongoing activities across the country include K-12 educational programs in schools, public astronomy evenings at colleges and universities, and activities coupled to NASA field centers and mission-related science institutes, NSF observatory and technology centers, and public or privately operated museums and planetariums. Efforts such as summer astronomy camps, after-school science activities, and community K-12 programs draw children into science at early ages. Public outreach activities such as lecture evenings, open houses, and star parties held at universities, observatories, and science conferences—and even at the White House (see Figure 4.5)—communicate the latest research developments and convey the excitement of the subject and the wonder of the night sky. The public outreach is impressive: in 2008, the 349 science centers and museums and 1,401 planetariums in the United States served 60.3 million people through onsite and online visits.[13]

Partnerships between professional research astronomers and professional educators at all levels build an important bridge between the classroom-based and informal education and outreach components of this effort. They can lead to particularly rewarding experiences by bringing first-hand knowledge of astronomical discovery directly to children.[14] In addition to the goal of improving national science literacy and proficiency in general, informal astronomy education and outreach activities may also be effective in attracting more minorities and girls into the sciences or science policy, which could help achieve demographic parity at more advanced career stages (Figure 4.7).

Astronomy Serves as a Gateway to New Technology

The long history of astronomy's contributions to society, and to the larger arena of science and technology, includes such modern examples as extension of the capability for developing experiments in X-ray astronomy for NASA in the 1960s to the manufacture of X-ray inspection systems for airports, military bases, and border

[13] Association of Science and Technology Centers (ASTC), *2008 ASTC Sourcebook of Statistics & Analysis,* February 2009, available at http://www.astc.org/pubs/source_book08.htm.

[14] For example, Project ASTRO, sponsored by the Astronomical Society of the Pacific, has more than 500 educator-astronomer partnerships nationwide that reach more than 20,000 students annually.

FIGURE 4.7 The interest of young girls and members of underrepresented minority groups in science can be cultivated through the public appeal of astronomy programs such as Sally Ride Science Festival Hands-on Workshops (*left*, experimentation with basic telescope concepts) and the Astronomical Society of the Pacific's Project Astro (*right*, appreciating black hole physics). SOURCE: *Left*—Courtesy of Sally Ride Science 2010 and Toni di Martino. *Right*—Courtesy of the Astronomical Society of the Pacific.

authorities. In addition to the applications mentioned above, image-processing techniques developed by astronomers are now in wide use in arthroscopic surgery, industrial applications, and even in tracking endangered animals. Scheduling software developed for the Hubble Space Telescope has now been adapted to optimize semiconductor manufacture and to manage patient flow in hospitals.

Astronomy and the America COMPETES Act

As the examples discussed above make clear, astronomy and astrophysics can make major contributions in all three areas highlighted in the America COMPETES Act:

1. *To strengthen research investment and to foster innovation and frontier research.* Astronomical research is transformative at the most fundamental level, exploring areas as far-reaching as the origin of the universe, the search for Earth-like planets in other solar systems, and the understanding of fundamental physical principles. Astronomy and astrophysics are drivers for innovation in technology, especially in optical systems, detectors, and data processing. Many of these tech-

nologies have found applications in the health sciences and national security. The major facilities and missions recommended in this survey will open new windows on the universe and will forge partnerships with both the private sector and international partners.

2. *To strengthen educational opportunities in science, technology, engineering, and mathematics (and critical foreign languages).* Astronomy has broad public appeal and vibrant ties to other branches of science and technology, strengths that enable the field to contribute to STEM education in uniquely powerful ways. As is mentioned above, college-level introductory astronomy courses are often the only science class taken by future K-12 teachers. Astronomical observatories and NASA missions have strong programs in informal science education, which can be a gateway to the sciences and have the potential to attract more minorities and women to the sciences and engineering.

3. *To develop a workforce for the 21st century*. Astronomy can play a central role in raising U.S. science literacy at all levels from kindergarten through university and across the general public as well. College-level introductory astronomy courses play a central role in teaching the scientific method. The depth and sophistication of engineering analysis required for today's new astronomical facilities and missions provide a unique opportunity for interns and young professionals to strengthen their skills.

CONCLUSION: Astronomical research continues to offer significant benefits to the nation beyond astronomical discoveries. These benefits include its role in capturing the public's attention and thereby promoting general science literacy and proficiency, its service as a gateway to science, technology, engineering, and mathematics careers, and a number of important and often unexpected technological spin-offs. The field of astronomy and astrophysics deserves inclusion in initiatives to enhance basic research, such as the America COMPETES Act.

Astronomy Addresses the Challenges of the 21st Century

The examples above show that astronomy contributes in unexpected ways to national agendas that extend far beyond the study of the universe itself. In science and technology today, two of the most important challenges are the impact of global climate change and the search for clean, sustainable, carbon-free sources of energy. In his address to the National Academy of Sciences in April 2009, President Obama issued a call to action, exhorting the United States to muster its collective expertise and energy to assume international leadership in addressing these challenges.

Astronomy has already played a major role in our understanding of global climate and climate change. The first understanding of the planet-wide greenhouse effect came from studies of Venus, whose surface temperature exceeds 800 degrees Fahrenheit because of a thick atmosphere of carbon dioxide. The first understanding of rapid global climate change came from computer models of the effects of nuclear war, and of catastrophic asteroid impacts that led to a mass extinction 60 million years ago. One of the best ways to investigate the complex problem of how Earth's climate responds to stress is to study the geological record of changes induced by periodic changes in Earth's orbit over the past few million years. A better understanding of the Sun is also critical to modeling and understanding climate change. Over the past few decades, as computational power has increased, our fundamental understanding of how the Sun works has been improving dramatically.

One of the most ambitious efforts to solve the nation's energy problems involves the development of controlled nuclear fusion. Nuclear fusion was first understood early in the last century by astronomers seeking the energy source of the stars, and since then there has been a close and fertile collaboration between astrophysicists trying to understand the behavior of plasmas in astrophysical systems and fusion researchers working to control plasmas in the laboratory; indeed, the U.S. fusion program was started by the same astronomer, Lyman Spitzer, Jr., who first proposed the concept of a space telescope.

Astronomers can bring to these initiatives their relevant experience, capabilities, and expertise in the atmospheres of planets and stars, radiative transfer, fluid dynamics, nuclear physics, plasma physics, electronics, detectors, remote sensing, numerical simulation of complex systems, and data handling, as well as one of their most important skills—the ability to draw reliable inferences from incomplete observations as opposed to controlled experiments.

CONCLUSION: Astronomy is a pure science, driven by human curiosity. Nevertheless, the techniques and models developed in the process of conducting astronomical research often have broad utility. Advances in understanding of the Sun and of the climates of other planets help illuminate critical issues and inform thinking about climate change here on Earth. The impact of recent discoveries and the many new opportunities that they have created have led to great interest in astronomy.

Astronomers and Public Policy

One of the more important communication challenges for science as a whole and astronomy in particular is in the area of public policy. Given that the practical outcomes of scientific investigations often play a key role in our economic prosperity and quality of life, and as scientific projects grow in size and complexity, it is important and useful for scientists and people with technical backgrounds to be engaged in the public policy process and to understand constraints in the funding of research.

Suitably skilled scientists can play important roles in government. Astronomers in particular can take greater advantage of the opportunities for engagement in public policy issues and advocacy for astronomy provided by the American Association for the Advancement of Science (AAAS), the AAS, and the American Physical Society (APS), as well as opportunities to participate in congressional visits, to hold congressional fellowships, to serve on advisory committees to the federal agencies, and to serve as rotators or staff members at the federal agencies and other national research infrastructure organizations. There is a need to educate and expose graduate students and postdoctoral scholars to issues of public policy and related processes. Astronomers serving in such positions would facilitate a better dialog between policy makers and working scientists and would help inform decisions about astronomy funding. Astronomy departments should be receptive to astronomers desiring to participate in the governmental process through such service.

RECOMMENDATION: The astronomical community should encourage and support astronomers' commitment to serve in science service and science policy positions, on a rotator, fellowship, or permanent basis, at the relevant funding agencies—NSF, NASA, DOE—in Congress, at the Office of Management and Budget, or at the Office of Science and Technology Policy.

ASTRONOMERS

Demography

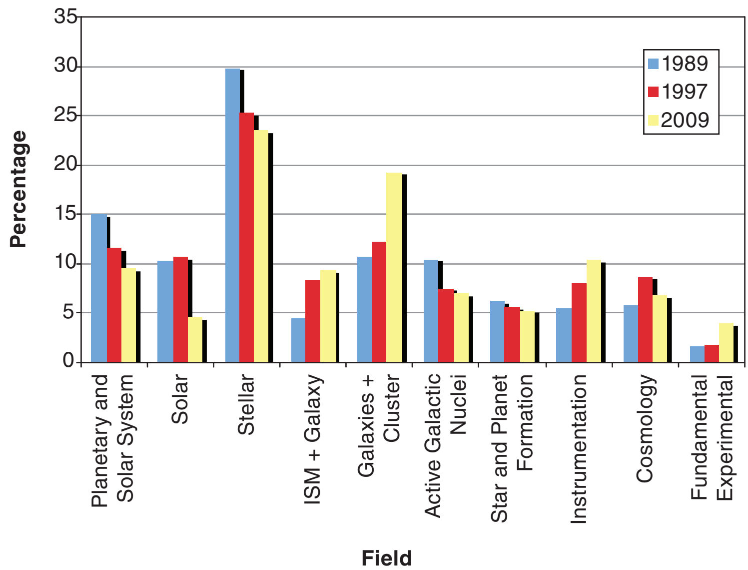
Revolutionary discoveries and new scientific opportunities have made astronomy and astrophysics a rapidly growing field of research. It is attracting scientists from other fields (e.g., high-energy physics), creating interfaces with other fields (e.g., astrobiology), and evolving in style (e.g., becoming more collaborative and more digital, and using more complex facilities). Table 4.1 and Figures 4.8, 4.9, and 4.10 detail how the field is changing. Conducting astronomical research increasingly requires detailed knowledge across many subfields of physics as well as knowledge of statistics and computational methods. In addition, with the increasing complexity of astronomy and astrophysics projects, both in space and on the ground, has come a greater need for expertise in areas such as instrumentation, project management, data handling and analysis, astronautics, and public communication—a development requiring broader training. Even as the field has become more vibrant and exciting, this time of change in astronomy has also induced some stress in the profession, particularly with regard to the careers of young scientists.

The number of astronomers is rising. The total membership of the AAS in all categories increased from 4,200 in 1984 to 7,700 in 2009, a growth of more than 80 percent in 25 years (roughly one-third of this growth is in graduate student mem-

TABLE 4.1 AAS Member Affiliation by Discipline, Field, and Location (percentage) for 1989, 1997, and 2009

	1989	1997	2009
Discipline			
Observational radio	13.7	10.4	8.9
Observational infrared	7.6	5.7	10.3
Observational optical	36.5	34.6	44.3
Observational ultraviolet	5.0	6.5	2.6
Observational high energy	5.6	8.7	11.6
Experimental particles and fields	1.1	1.3	1.3
Laboratory astrophysics	2.2	2.2	0.1
Theory	23.8	23.9	16.7
Administration	1.7	3.5	0.4
Education and public outreach	N/A	N/A	2.5
Amateur or historian	2.6	3.0	0.6
Aeronomy	0.3	0.4	0.5
Field			
Planetary and solar system	15.0	11.6	9.5
Solar	10.3	10.7	4.6
Stellar	29.9	25.4	23.6
Interstellar medium + galaxy	4.4	8.3	9.4
Galaxies + cluster	10.7	12.2	19.3
Active galactic nuclei	10.5	7.5	7.0
Star and planet formation	6.3	5.7	5.3
Instrumentation	5.5	8.1	10.4
Cosmology	5.8	8.7	6.8
Fundamental experimental	1.6	1.8	0.4
Location			
Research university	47.4	47.5	44.1
College	8.4	10.1	15.1
Federally funded research and development center	9.9	11.2	11.9
Government laboratory	18.8	19.8	22.2
Private observatory	3.8	2.7	2.8
Industry	8.0	6.0	3.0
Education and public outreach	N/A	N/A	0.4
Other	3.7	2.7	0.5

NOTE: Statistics on demographics based on a sampling of approximately 20 percent of American Astronomical Society (AAS) full members in the given year. The 1989 and 1997 statistics for 714 and 599 full members, respectively, are from the NRC's 2000 *Federal Funding of Astronomical Research* (FFAR) report (National Academy Press, Washington, D.C.). The counting uncertainties are approximately 1 to 2 percent. For direct comparison to the FFAR methodology, the statistics for 2009 were derived by selecting 800 full members of the AAS at random and matching their names against the FFAR literature search. Affiliation was identified either by the address provided in the AAS database or by the affiliation listed on the most recent publication. N/A, not applicable.



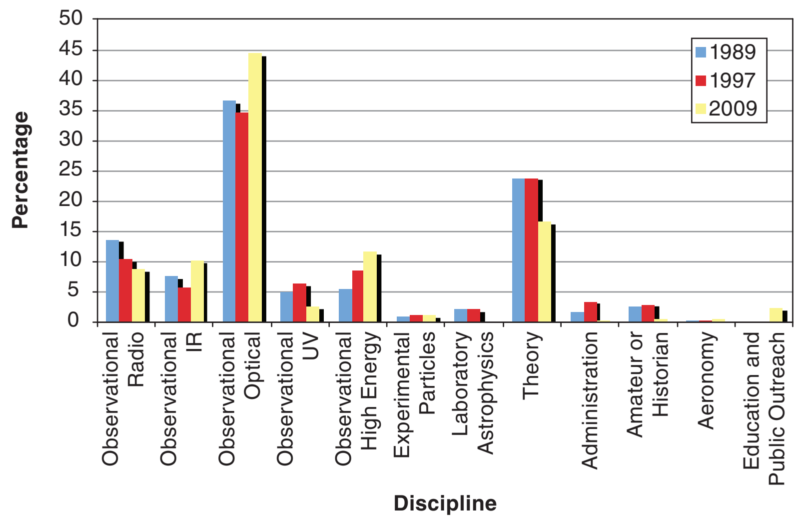


FIGURE 4.8 Employment of American Astronomical Society members in 1989, 1997, and 2009 by field (*top*) and discipline (*bottom*). Note that data for employment in education and public outreach were not available for 1989 and 1997. SOURCE: Data from the American Astronomical Society.

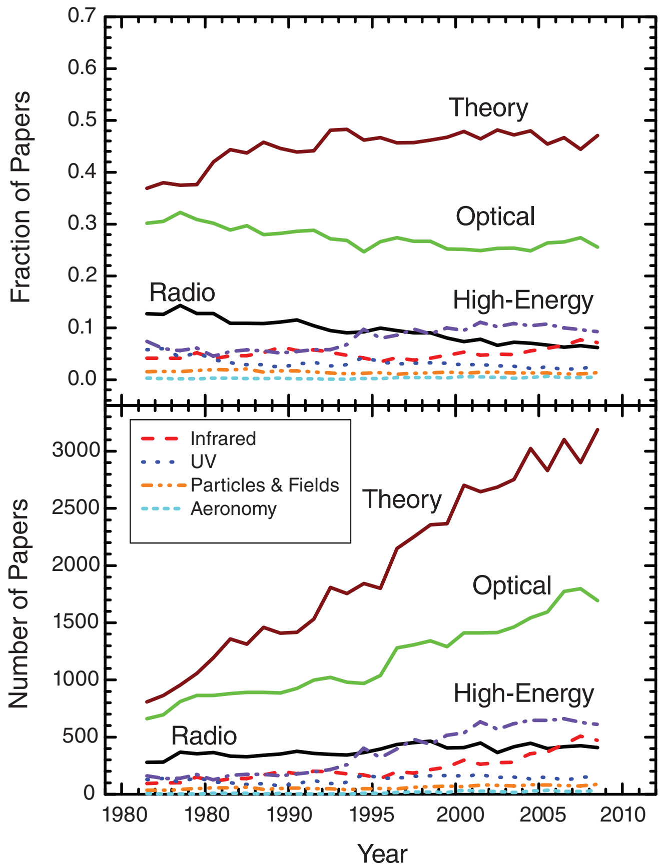


FIGURE 4.9 Papers published in journals on the FFAR list (National Research Council, *Federal Funding of Astronomical Research,* National Academy Press, Washington, D.C., 2000), 1981 to 2009. *Top:* Papers in specific disciplines as a fraction of all papers published. *Bottom:* Absolute number of papers published per year. Disciplines were assigned by Bayesian classification on the basis of title, abstract, and keyword text extracted from the Astrophysical Data System. The reported fractions are annual averages.

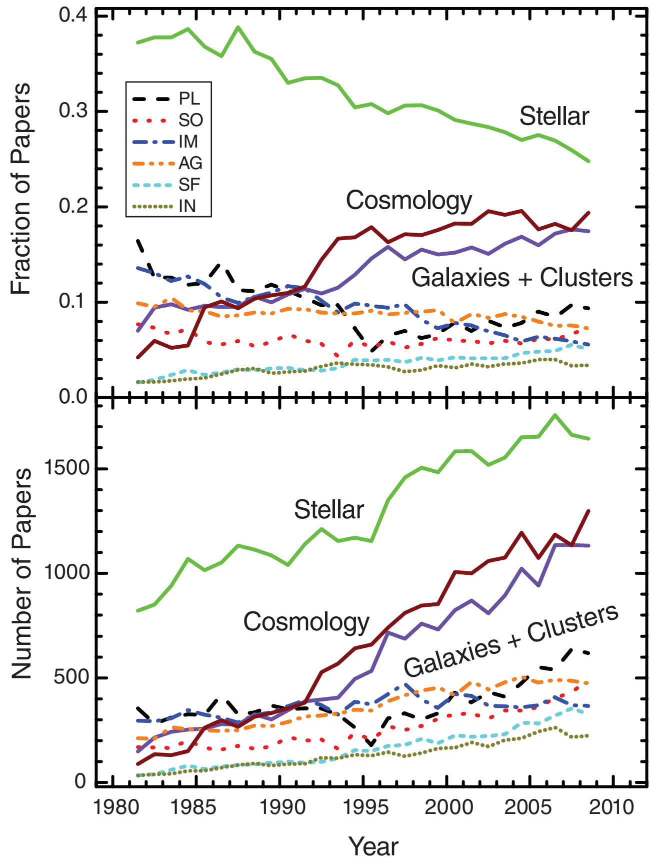


FIGURE 4.10 Papers published in journals on the FFAR list (National Research Council, *Federal Funding of Astronomical Research,* National Academy Press, Washington, D.C., 2000), by field. *Top:* Papers in specific fields as a fraction of all papers published. *Bottom:* Absolute number of papers published. Fields were assigned by Bayesian classification on the basis of title, abstract, and keyword text extracted from the Astrophysical Data System. NOTE: PL, planetary and solar system; SO, solar; IM, interstellar medium and the galaxy; AG, active galactic nuclei; SF, star and planet formation; and IN, instrumentation. The reported fractions are annual averages.

bers), while the U.S. population at large has increased by only 30 percent over that period. The total number of professional astronomers is estimated to be even larger, around 9,000 based on the decadal survey's own data gathering on demographics (Figure 4.11), since there are many more members of the American Geophysical Union (AGU), the APS, and the Optical Society of America who work in subfields like extrasolar and solar system planetary science, cosmology, and instrumentation who are not members of the AAS.

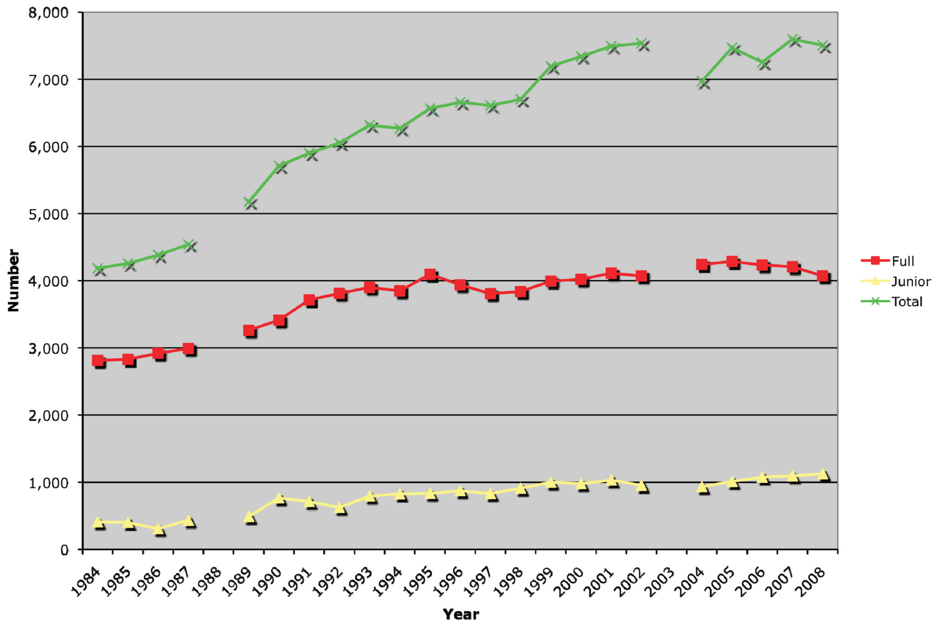


FIGURE 4.11 American Astronomical Society membership (U.S. and international) from 1984 through 2009. Data for 2009 are based on a sample taken in March 2009, and numbers were expected to increase. Associate members and division or international affiliates are not shown separately. The total number of members increased by 33 percent from 1990 to 2006 (junior members increased by 43 percent and full members by 23 percent); census data (U.S. Bureau of the Census, online reports) indicate that the U.S. population increased by 20 percent in the same period. SOURCE: Data from the American Astronomical Society.

About 44 percent of AAS members in 2009 were affiliated with research universities, and 34 percent were affiliated with national observatories, laboratories, and other federally funded research and development centers (see Table 4.1). The fractions in different work sectors have not varied much over the past 20 years except at 4-year colleges, where the fraction of astronomers has almost doubled (to 15 percent), reflecting the growing importance of introductory astronomy as a gateway science course and as a popular course for non-science majors to fulfill a science requirement.

The annual number of astronomy Ph.D.s awarded in the United States has been fairly constant at about 200 over the past decade, compared with approximately 1,400 in physics and 4,000 in the physical sciences overall. However, increasing numbers of astronomers are receiving their degrees from physics departments. The fraction of astronomy Ph.D.s awarded in the United States to non-U.S. citizens has risen from about one-quarter to more than one-third over the past decade, still slightly behind the fraction for physical sciences overall. Although many foreign astronomers are expected to repatriate, the globalization of research, discussed above, ensures that many are likely to continue to contribute to the U.S. astronomical enterprise.

About 70 percent of the astronomy Ph.D. holders who remain in the United States after obtaining their degrees hold fixed-term postdoctoral positions before gaining long-term employment (Figure 4.12). Some postdoctoral positions are prize fellowships supported either by agencies (e.g., NASA's Einstein, Hubble, and Sagan fellows; NSF's Jansky fellows through NRAO and astronomy and astrophysics postdoctoral fellows) or by private donations to individual universities. These highly competitive fellowships allow independent research programs in a large range of subfields. Other postdoctoral positions are tied to a specific sponsored research grant or project. It is quite common for astronomers to hold two or three successive postdoctoral positions of 2 to 3 years each, so that many astronomers are in their mid- to late-30s before finding long-term employment. One consequence of this delay is the added difficulties for family life, which can also compound the problem of attracting women to the field.

Data from the AAS Job Register indicate that the number of postdoctoral positions advertised every year has doubled over the last decade, whereas the number of advertised tenure-track positions and long-term research or support positions[15] has decreased slightly. Some of these positions are taken by foreign applicants, and some U.S. postdoctoral scholars take up employment elsewhere. Overall, the production rate of astronomy Ph.D.s exceeds the current rate of long-term astronomy faculty opportunities by a factor of at least three, which is a point of great concern to young astronomers (Figure 4.13). Recently this problem has become much more acute because of a decrease in the number of faculty openings due to hiring freezes and postponements of retirement for economic reasons. However, from the data shown in Table 4.1 plus an understanding of the diverse set of job functions held by those at research universities, it can be inferred that traditional teaching faculty positions are less than half of the permanent positions held by AAS members.

Astronomy is an incredibly exciting field that is attracting some of the best and brightest technically able young people. They are a precious resource for the nation, and it is important to optimize and broaden the benefits to the nation that their talents bring. Young people trained in astronomical research have a high degree of competence in disciplines with applicability beyond just astronomy and astrophysics. As a group, they are also energetic, hard-working, and highly motivated, and the fraction of their time that can be devoted to research is higher than at earlier and later career stages.

[15] The support jobs are very valuable to the astronomy enterprise and include employment in observatories, federal agencies, and schools. Not all of these jobs require a Ph.D.

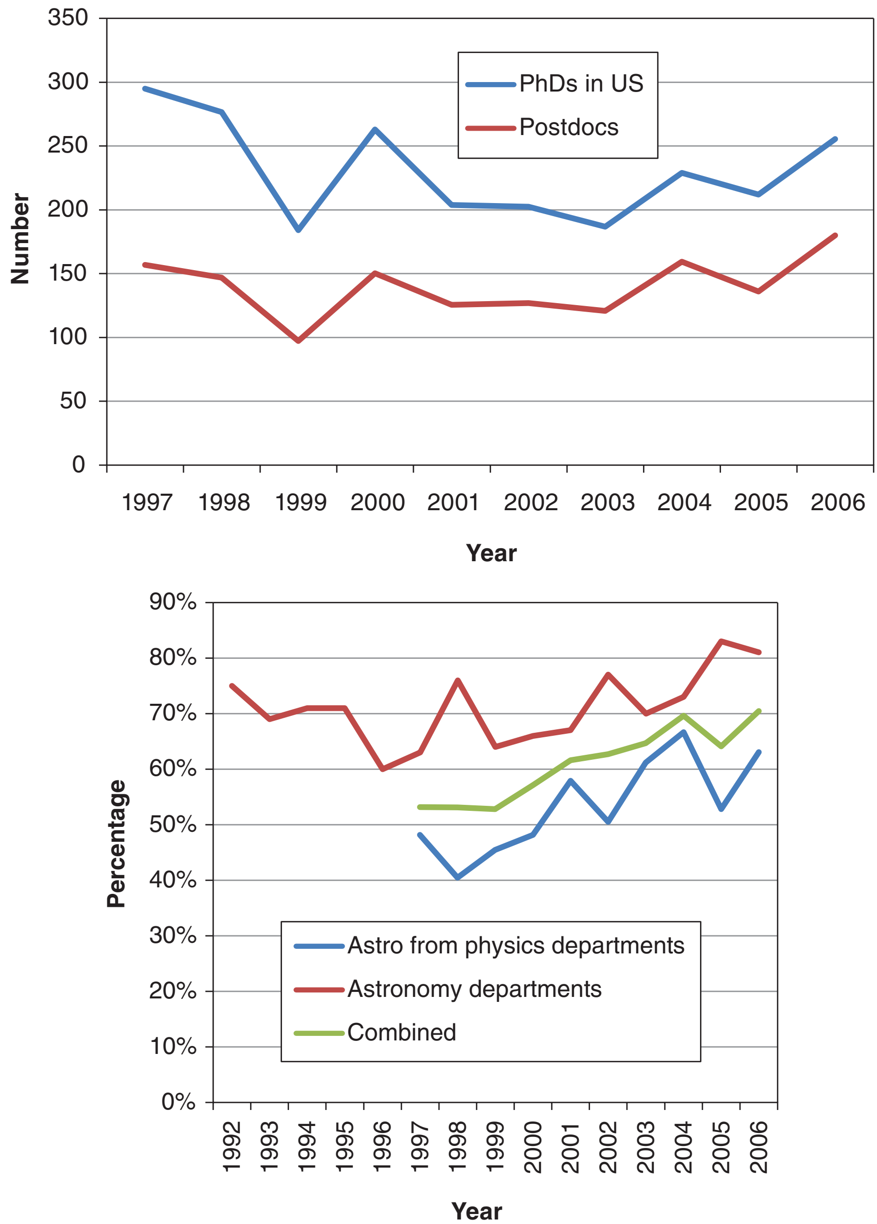


FIGURE 4.12 Number (*top*) and fraction (*bottom*) of postdoctoral positions taken by astronomy and astrophysics Ph.D. recipients who remained in the United States, 1997 to 2006. The data include Ph.D.s from astronomy departments and Ph.D.s from physics departments who reported the following specialties: (1) astrophysics; (2) atmospheric, space, and cosmic-ray physics; and (3) relativity and gravitation. SOURCE: Initial Employment Survey, Statistical Research Center, American Institute of Physics.

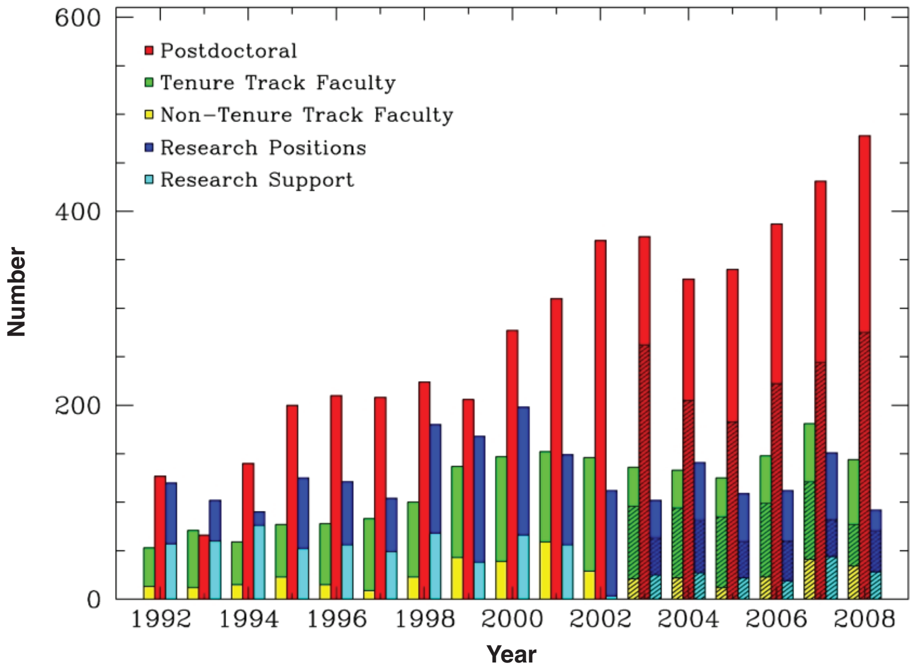


FIGURE 4.13 Number of postdoctoral (red), faculty (green/yellow), and research (blue/cyan) positions advertised from 1992 to 2008. Shading indicates the number of positions in each category at U.S.-based institutions after such data became available in 2003. The faculty category is divided into tenure track (green) and non-tenure track (yellow) positions; the research category is divided into research (blue) and support (cyan) positions. Data from the American Astronomical Society.

Although training in astronomy for astronomers is valuable, in practice at least 20 percent of astronomers leave the profession for other careers following the Ph.D., the postdoctoral, and even the faculty/research position level. Careers outside astronomy and astrophysics are available that make use of the technical expertise gained through an astronomy education, and astronomers are demonstrably employable in a large variety of professions, such as computer science, data systems, image processing, detector technology, and medical technology, as well as other physical sciences.

Implications for Employment and Training

Training in astronomy research is good preparation for a wide range of careers. Experience in finding innovative solutions to new problems and familiarity with cutting-edge techniques and tools have very broad appeal to employers, and an astronomer's education is rarely wasted. Nonetheless, the recent rapid growth in the postdoctoral pool of temporary positions suggests an increased need for advising and mentoring regarding broad career choices, not just in academia but also across the education and research enterprise, including careers beyond astronomy. Indeed, there is a strong and urgent need for career mentoring at all stages, from undergraduate to junior faculty member. In addition, it is important to introduce courses into astronomy curricula that can open doors to new careers. These courses could involve computer science, engineering, project management, public policy, or pedagogy, for example, possibly taken in other departments.

Often, academic mentors emphasize academic careers for their students at the expense of discussing and supporting a broader range of career opportunities. The committee believes that doctoral training in astronomy prepares an individual for a variety of rewarding and important STEM careers and that the astronomy community needs to recognize alternate career paths more clearly.

Professional training should accommodate the range of career paths taken by graduate and postdoctoral alumni, giving attention to (1) the full range of activities in academic faculty work, including teaching, advising, and performing institutional and national service; (2) the non-research skills needed by all researchers, including communicating to the non-specialist and the public at large, writing and administering grants, and project management; (3) necessary high-level training in communication and in the increasingly important areas of computation and instrumentation; and (4) career options both within and outside academia. Some of these goals could be achieved through professional master's programs in astronomy with a particular focus. Partnership opportunities with government, industry, media resources, and museums could help broaden astronomy-related experiences through internships in areas such as public policy, computation and instrumentation, pedagogy, science outreach, and communications.

RECOMMENDATION: The American Astronomical Society and the American Physical Society, alongside the nation's astronomy and astrophysics departments, should make both undergraduate and graduate students aware of the wide variety of rewarding career opportunities enabled by their education, and be supportive of students' career decisions that go beyond academia. These groups should work with the federal agencies to gather and disseminate demographic data on astronomers in the workforce to inform students' career decisions.

Underrepresented Minorities in Astronomy

Black Americans, Hispanic Americans, and Native Americans constitute 27 percent of the U.S. population. By all measures they are seriously underrepresented among professional astronomers. For example, this cohort accounts for only 4 percent of astronomy Ph.D.s awarded in the United States and 3 percent of faculty members, and yet even these small fractions represent growth. To achieve parity would require increasing the annual rate of minority Ph.D.s in astronomy from around 5 percent to a sustained value of about 40 percent over a period of 30 years.[16]

There are many reasons that improving these abysmal statistics should be a matter of the highest priority. First, failing to tap into such a large fraction of the population is hurting the country through not accessing a large human resource, and this is a statement applicable also to science in general. Second, because of the prominent position of astronomy in the public eye, the absence of minority role models sends a strongly negative message to young people considering careers in science and engineering. The Committee on the Status of Minorities in Astronomy of the AAS works as both a focus and an information dissemination group for these important issues and as a support and mentoring group for minority members of the AAS.

There have been many well-intentioned and thoughtful programs over the past decades to increase minority representation in astronomy and other scientific fields, but they have not yet succeeded in achieving the goal of equal representation in the Ph.D. scientific workforce. There has been some success in increasing the number of minorities who obtain bachelor's degrees in science and engineering, to about 18,500 in 2007.[17] However, minority groups remain underrepresented at the master's and Ph.D. levels and in the professional workforce in these fields. This underrepresentation might be overcome by creating programs to bridge minority undergraduates from physics, computer science, and engineering into master's programs that would allow them to enter the astronomical workforce directly or to move on to a Ph.D. Given the increasing numbers of minority undergraduates in physics, computer science, and engineering and the current workforce needs in astronomical computation and instrumentation, recruitment into astronomy and astrophysics careers and Ph.D. programs could be pursued.

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[16] D. Nelson and L. Lopez, The diversity of tenure track astronomy faculty, *Spectrum*, American Astronomical Committee on the Status of Minorities in Astronomy, June 2004, available at http://csma.aas.org/spectrum.html; the AIP Academic Workforce Survey and the AIP Statistical Research Center (see http://www.aip.org/statistics/). For comparison, AIP data for 2007 indicate that 5,402 U.S. citizens received Ph.D.s and that 13 percent were awarded to members of minorities (http://www.aip.org/statistics/trends/highlite/edphysund/table8.htm; accessed July 7, 2010) and of the 653 physics Ph.D.s awarded to U.S. citizens, 13 percent were awarded to members of minorities (http://www.aip.org/statistics/trends/highlite/edphysgrad/table6.htm; accessed July 7, 2010). In 2007, across all disciplines, including non-science disciplines, the number of faculty positions held by African Americans or Hispanic Americans was about 11 percent, and about 5 percent in physics disciplines (http://www.aip.org/statistics/trends/highlite/awf08/table1a.htm; accessed July 7, 2010).

[17] See http://www.nsf.gov/statistics/wmpd/degrees.cfm.

One way to accomplish such a transition would be to encourage strategic partnerships[18] with minority-serving institutions (MSIs) including historically black colleges, as well as with the National Society of Black Physicists and the National Society of Hispanic Physicists. A related path would be to encourage graduate programs to recruit their master's and Ph.D. candidates at MSIs.

Role models are important in any field and have been particularly crucial in improving the number of women astronomers. Using the Harlow Shapley Visiting Lectureship Program[19] proactively to target students in MSIs, and rebuilding NASA's Minority University Research and Education Program[20] to engage STEM students in mission-related work, are two approaches that have provided role models to minorities. Finally, the committee suggests that the federal agencies establish a competitive program of summer programs and leaves of absence for teachers from MSIs with a proven record of educating minority scientists, to participate in research at national facilities and research universities. Programs like this, if thoughtfully managed, would provide a bridge for minority students from a bachelor's to an advanced degree. It is important that the success of such programs be monitored and that rigorous metrics for success be established at the outset, providing an opportunity for longitudinal tracking of minority students and learning how to improve programs through their experience.

CONCLUSION: Little progress has been made in increasing the number of minorities in astronomy. Agencies, astronomy departments, and the community as a whole need to refocus their efforts toward attracting members of underrepresented minorities to the field.

The following are some approaches that can be adopted to help in attracting members of minorities to astronomy and in retaining them in the field:

- Targeted mentoring programs;
- Partnerships of community colleges and minority-serving institutions with research universities and with national centers and laboratories;

[18] Promising examples of programs along these lines have been established at the University of Washington, at Columbia University, and in a partnership between Vanderbilt University and Fisk University.

[19] The Harlow Shapley Visiting Lectureship Program of the American Astronomical Society is a program of 2-day visits by professional astronomers who bring the excitement of modern astronomy and astrophysics to colleges of all types. See http://aas.org/shapley.

[20] NASA's Minority University Research and Education Program (MUREP) engages underrepresented populations through a wide variety of initiatives. Multiyear grants are awarded to assist minority institution faculty and students in research of pertinent missions. See http://www.nasa.gov/offices/education/programs/national/murep/home/index.html.

- Expanded funding for programs that ease the transition of individuals across critical junctures in the pipeline—high school to college, community college to university, undergraduate to graduate school;
- Funding for master's-to-Ph.D. programs;
- Cross-disciplinary training as an on-ramp to astronomy and astrophysics careers; and
- Family-friendly policies.

Women in Astronomy

Historically, women were once as underrepresented in professional astronomy as minorities are today, especially as faculty members. Now, there is ongoing progress toward parity, although still shortfalls relative to the general population. The fraction of astronomy graduate students that are women has increased from a quarter to a third over the past decade, and the fraction gaining Ph.D.s and occupying assistant and associate professor positions is also a quarter. However, only 11 percent of full professors are women, fortunately a proportion that is likely to improve as more women advance up the ranks. The Committee on the Status of Women in Astronomy of the AAS works both as a focus group on these important issues and as a support and mentoring group for female members of the AAS across professional ranks.

The arguments for seeking gender equality parallel those for increasing the involvement of underrepresented minorities as professionals in the field. Interestingly, the NSF Research Experiences for Undergraduates (REU) program has achieved a participation rate for women of nearly 50 percent in astronomy summer research assistantships. To increase the number of women in the field, some schools have also taken the promising approach of identifying undergraduate women for master's programs that act as a bridge into the profession. The efficacy of these programs should be monitored, and if they prove to be successful such programs should be supported more widely. In addition, two identified pressure points for women can be addressed. The first is that in middle school, girls frequently lose interest in mathematics and science,[21] and astronomy can play a role in keeping young women interested in science through high school. After-school programs and camps supported by NSF, in particular, need to be assessed for their effectiveness in drawing girls into science. The second pressure point arises when professional and family obligations conflict and women, in particular, find their pursuit of an academic career derailed. Targeted mentoring programs and family-friendly education and employment policies can help to attract and retain women in astronomy. Practical steps that have been proposed include allowing parental

[21] See http://www.sallyridescience.com/.

leave, assisting with childcare, assisting with spousal employment, and allowing delay of the tenure clock.[22]

CONCLUSION: The gender gap in astronomy has diminished significantly, although women still occupy only a small percentage of the most senior positions. Astronomy departments and the community as a whole need to continue work to promote gender equity at all levels.

[22] The "Pasadena Recommendations" of the National "Women in Astronomy" meeting in 2003 were endorsed by the American Astronomical Society.

5

Sustaining the Core Research Program

A great strength of the astronomy and astrophysics research enterprise in the United States is that support comes from a variety of sources. These include federal and state governments as well as private universities, foundations, and individual donors. The federal program, with which this report is most concerned, is managed by NSF, NASA, and DOE, with additional, directed federal funding coming through the Smithsonian Institution[1] and the Department of Defense.[2] The research enterprise consists of two main components: (1) unique facilities, missions, and institutions, which are discussed in Chapter 6, and (2) the broadly distributed core activities discussed in this chapter—such as research grants to individuals and groups that support observation, theory, computation, data handling and dissemination, technology development, and laboratory astrophysics—that are the true foundations of the astrophysics enterprise.

Maintaining the correct balance between large and small projects, between projects and core activities, and also among the elements of the core program is a challenge that requires evaluation in the context of the current and future scientific landscape. In its review of the current health of these activities, the committee identifies modifications or augmentations that, because of an evolution of funding,

[1] This report does not review the activities of the Smithsonian Astrophysical Observatory, which operates with a federal appropriation of roughly $24 million (FY2009).

[2] This report does not review activities of the Department of Defense, which provides support in areas such as solar physics, astrometry, and interferometry, including support for the activities of the United States Naval Observatory.

of science, or of infrastructure, are needed to maintain the balance that is essential for a vibrant astronomy and astrophysics research program.

INDIVIDUAL INVESTIGATOR PROGRAMS

Individual investigator programs are paramount in realizing the science potential of existing facilities, in pathfinding for future space missions and ground-based projects, and in training the current and future workforce. A healthy enterprise in astronomy and astrophysics requires a vigorous research grants program.

The fundamental products of astronomy (or any other science) are the discoveries resulting from research—new testable and tested ideas. The data analysis and dissemination and theoretical work performed by both individual scientists and science teams are ultimately responsible for the amazing results witnessed in astronomy in the past few decades. One of the most important secondary products is people who are trained in the broad discipline of science and who have skill in quantitative thinking and analysis, numerical computation, instrumentation and engineering, teaching, and project management.

Astronomers use complex and sophisticated tools and facilities such as satellites (e.g., the Hubble Space Telescope, the Chandra X-ray Observatory, the Spitzer Infrared Observatory, the Fermi Gamma-ray Space Telescope), ground-based facilities (e.g., NRAO plus ALMA, NOAO plus Gemini telescopes), and computing (high-performance networks, large-scale clusters, and software) to produce these products. However, supporting the development, construction, and operation of astrophysics facilities is far from all that is required to produce the superb results and discoveries that have driven the field and captured the public's imagination. It is the *combination* of improved capabilities and facilities and the resources to use them effectively that has led to the remarkable scientific advances in astronomy. Scientific progress thus depends on and requires that individual investigators be supported, including being granted the resources that train students and postdoctoral fellows.

A significant challenge for the astrophysics program is how to maintain support for individual investigators pursuing a broad range of activities in a landscape where specific, large programs provide a fluctuating level of funding for associated analysis and theory. Realizing the scientific potential of existing facilities is of primary importance, but so is placing the broad range of results in appropriate context, providing young scientists with opportunities to develop their potential, and enabling the creative thinking that lays the foundations for the future.

As in most fields, the primary mechanisms for supporting research and training are competed grants programs. NASA funds both general mission-enabling grants programs and those supporting the specific science from operating satellites, such as the guest observer programs associated with Hubble, Chandra, Spitzer,

TABLE 5.1 NASA Astrophysics Division-Sponsored Proposal Opportunities for 2007

Program	Proposals Received	Proposals Selected	Oversubscription Rate
Astronomy and Physics R&A (APRA)	146	52	2.8 to 1
Hubble Space Telescope	821	189	4.3
Chandra X-ray Observatory	663	177	3.7
Spitzer Space Telescope	720	258	2.8
XMM-Newton	330	102	3.2
INTEGRAL	30	25	1.2
Kepler Participating Scientists	37	8	4.6
Origins of Solar Systems (with Planetary Science Division)	104	27	3.9
Astrophysics Theory and Fundamental Physics (ATP)	181	37	4.9
GALEX Guest Investigator – Cycle 4	99	35	2.8
Astrophysics Data Analysis	98	41	2.3
Fermi Guest Investigator – Cycle 1	167	42	4.0
Swift Guest Investigator – Cycle 4	144	49	2.9
Suzaku Guest Investigator – Cycle 3	120	50	2.4
TOTAL	3,660	1,092	3.4

SOURCE: NASA Astrophysics Division.

and Fermi. NSF supports a general astronomy and astrophysics grants program as well as more specialized programs such as the CAREER awards and the Astronomy and Astrophysics Postdoctoral Fellow program. DOE supports centrally administered grants programs, those administered through specific DOE laboratories, and awards for young investigators.

In recent times, funding for these essential programs has flattened or even declined[3] at NASA and NSF, especially when considered relative to the growth of the field. Notably, DOE funding for astrophysics research increased from $34.4 million per year in 2004 to $45.2 million per year in 2008. Table 5.1 shows that in 2007 the oversubscription rate for various elements of NASA's Astrophysics Division grants program varied but generally exceeded 2.5:1 and was as high as 4.9:1. Figure 5.1 shows that during the past decade, NSF's proposal success rate for AST grants fell from a high of 37 percent in 2002 to a low of 23 percent in 2008, significantly lower than the more than 50 percent success rate of the early 1990s.

These data show that grant support for individual astronomers and astrophysicists has not grown as fast as the field over the past 15 years. At the current proposal success rate of less than 1 in 5 for NSF's AAG program or some of the NASA R&A grants programs, even proposals rated "excellent" cannot be supported. There is a strong case for increasing the funding of these programs such that those

[3] Funds provided by American Recovery and Reinvestment Act allocations to the agencies are a temporary perturbation of these trends.

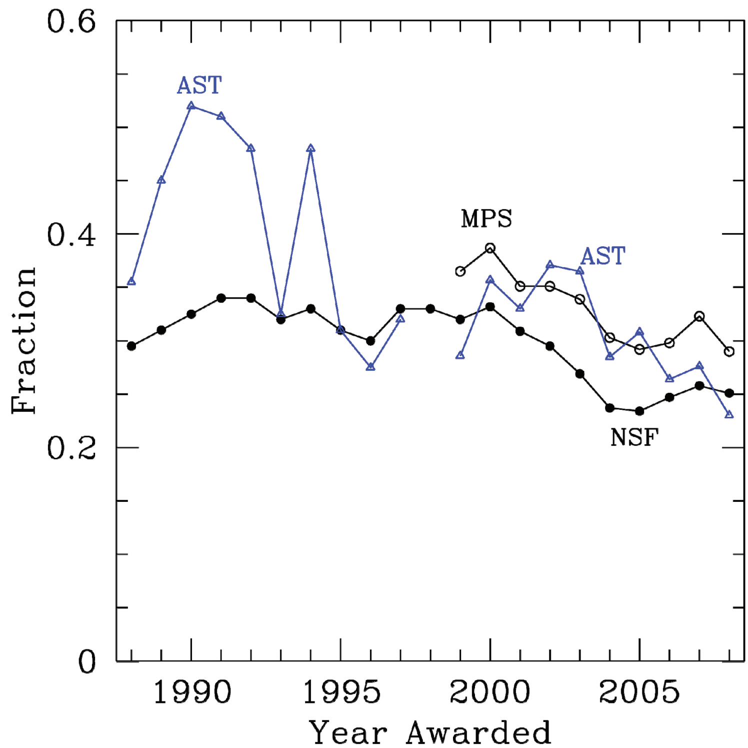

FIGURE 5.1 Proposal success rate for NSF as a whole, for NSF's Directorate for Mathematics and Physical Sciences (MPS), and for NSF's Astronomical Sciences (AST) Division, from 1988 to 2008.

proposals deemed worthy of funding by review panels, program managers, and advisory groups can be supported. Furthermore, the current situation is not a healthy position from which to carry out the more ambitious recommendations of Astro2010, given the needs for technical resources and personnel training. The goal is to achieve an appropriate balance between the optimal scientific exploitation of data obtained from the missions and facilities funded by NASA and NSF, and the mission/facility support itself.

In the committee's judgment, it is absolutely necessary for the health of the whole astronomy and astrophysics enterprise to increase the support of individual investigators: those who write the papers, who train the students and other junior researchers, and who in the end produce the results to drive the field forward and ignite the public's imagination. Reallocation of resources may have to come at the expense of support of existing missions/facilities and new projects.

In Chapter 7 the committee recommends upward adjustments in the funding levels of certain individual researcher and group grants programs at NSF and NASA. Funding opportunities and the changing needs of larger programs sometimes require advice on significantly shorter intervals than the long-term advice provided here on program balance. In the past decade, for example, changing priorities at NASA overall, combined with the Columbia disaster, resulted in an abrupt funding redistribution that ultimately led to a significant imbalance in NASA's astrophysics program, which in turn created issues with continuity of small-scale funding.[4] For such unforeseen changes in circumstance, the AAAC can, as discussed in Chapter 3, provide tactical advice to DOE, NASA, and NSF on the support of individual and group grants funding, including the balance between grants programs, mission/facility operations, and the design and development of new missions/facilities.

THEORY

Emerging Trends in Theoretical Research

The role of theory in astrophysics has evolved in ways that reflect the increasing complexity of observations. Today, theoretical astrophysicists use analytical methods to devise speculative scenarios that account for new observations, they carry out detailed computational simulations of complex systems, and they develop new methods and frameworks for testing models against observational data. Together these methods propel progress, often in unforeseen ways. For example, the discussion of gravitational microlensing in the 1980s led to new observational constraints on the nature of dark matter in the 1990s and now provides a powerful pathway to the discovery of exoplanets. Similarly, recent observations of the cosmic microwave background have provided precision measurements of the age and content of the universe, but only because the theoretical framework had been developed over the preceding several decades, starting with new, bold theories about the exponential expansion rate of universe in its first few moments. Moreover, theory informed the design of experiments and enabled measurements to be extracted. The result is a spectacularly successful "standard model" of the universe, which experiments recommended in this report will test even more stringently.

Several important trends are increasing the scope of theoretical activity and enhancing the roles of theorists:

- The boundary between astrophysics theory and high-energy physics theory has become increasingly blurred as astrophysical observations play a growing role in particle physics phenomenology. Much of the information we

[4] National Research Council, *A Performance Assessment of NASA's Astrophysics Program,* The National Academies Press, Washington, D.C., 2007.

have about physics beyond the standard model of particle physics comes from astrophysics; particle and astrophysical theorists are collaborating to push back the frontiers of fundamental physics. As an example, particle physics theory provides the prime candidates for potential dark matter particles (weakly interacting massive particles and axions) with properties that are constrained by both high-energy physics and cosmology.

- Large numerical simulations are increasingly central to progress in astrophysics. Rapid advances in computational capabilities enable the large-scale computations needed to understand the complex phenomena being uncovered by current telescopes. They will be essential for predicting and understanding gravitational wave signals, and will enable three-dimensional simulations of supernova explosions and of the formation of the first stars in the universe, for example (Figure 5.2).
- As the cost and scope of new observational facilities have grown, theorists have played an increasing role in their conceptual development, in making the science case for funding them, and in analyzing the results. Examples include new gravitational wave observatories and modeling of the distribution of stable planetary systems to inform future searches.
- Theorists provide visualizations of complex physical phenomena that facilitate deeper understanding, that are appealing to the general public, and that attract talented young people to the field.

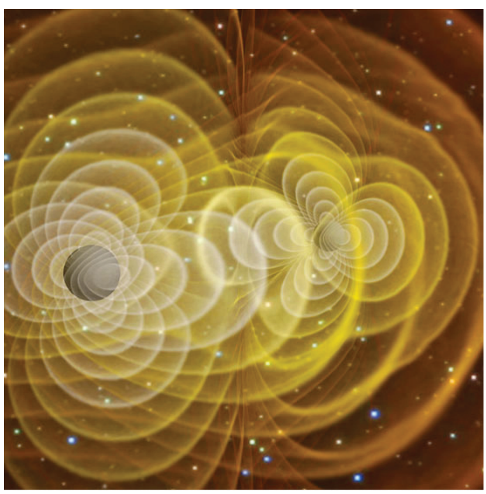

FIGURE 5.2 Simulated image of gravitational radiation from two merging black holes using NASA's Columbia supercomputer. A movie of this simulation can be found at http://www.nas.nasa.gov/News/Archive/2006/08-09-06.html. SOURCE: Chris Henze, NASA.

Theoretical Challenges for the Next Decade

A healthy theory program advances science on a broad front and supports a range of targeted activities as well as the exploration of radical new ideas that inspire missions for the distant future. For this decade, the Astro2010 Science Frontiers Panels (SFPs), and Chapter 2 of this report, have identified questions on the forefront of astrophysics, several of which present specific and significant theoretical challenges.

The Panel on Cosmology and Fundamental Physics raises the questions, How did the universe begin? Why is the universe accelerating? What is dark matter? What are the properties of neutrinos? New observations are central to providing the necessary constraints to address these questions, but theories are ultimately being put to the test.

One of the upcoming challenges associated with the Panel on Stars and Stellar Evolution is the three-dimensional simulation of the magnetic field observed in the solar corona using the Solar Dynamics Observer and other solar observatories. The quality of the data now being garnered presents a strong challenge to simulators. Success in explaining the behavior of the solar magnetic field will pay large dividends as astrophysicists attempt to understand how fields behave in other environments.

The prime research topics identified by the Panel on the Galactic Neighborhood involve study of the circumgalactic and interstellar media seen as complex ecosystems. For both topics, sophisticated simulations go hand in hand with the observational program. A third question concerns the fossil record of star formation as a means of understanding the first stars and the subsequent assembly of galaxies like our own. Here the theories of stellar evolution and stellar dynamics are crucial. The fourth research area, the use of the galaxy to study dark matter (Figure 5.3), has already attracted the attention of a large community of theoretical physicists.

Central questions raised by the Panel on Galaxies Across Cosmic Time are the following: How do cosmic structures form and evolve? How do baryons cycle in and out of galaxies, and what do they do while they are there? How do black holes grow, radiate, and influence their surroundings? (Figure 5.4), and What were the first objects to light up the universe, and when did they do it? As discussed below, analytic theory and computational modeling will take a central role in addressing these questions.

Supernovae are the most energetic explosions in the universe since the big bang and the furnaces in which most of the chemical elements from which we are made are forged. Visible from halfway across the universe, these spectacular cosmic events provide some of the strongest evidence that the universe is accelerating. As pointed out by the Panel on Stars and Stellar Evolution, understanding why and how stars

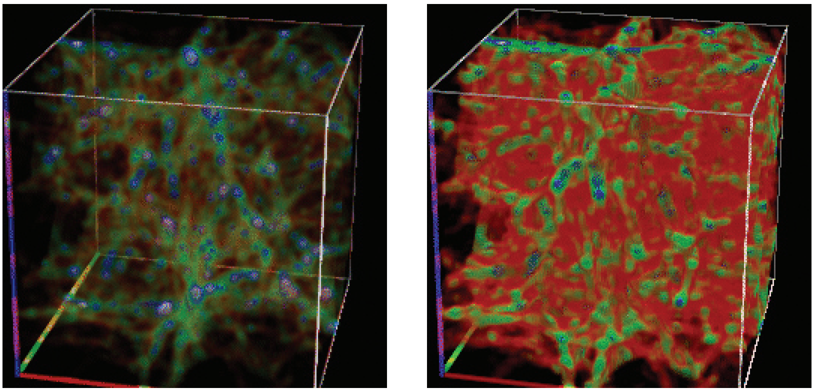

FIGURE 5.3 Two views of dark matter distribution. SOURCE: Edmund Bertschinger, MIT.

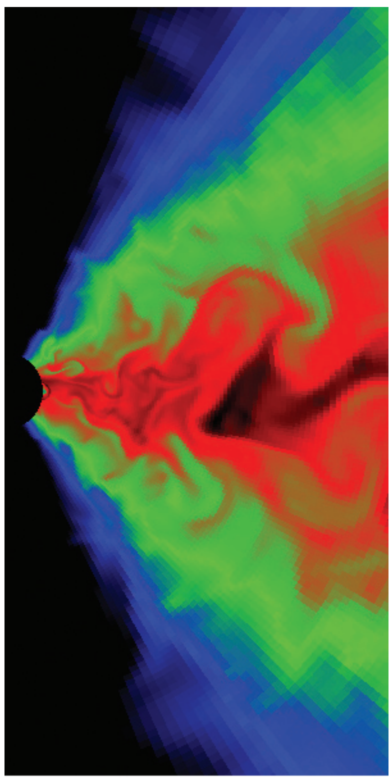

FIGURE 5.4 False-color simulated image of the density of matter accreting from a spinning gas disk onto a black hole. The image shows a cross-sectional cut through one side of the disk, with the black hole represented as a black semicircle on the left side. A striking feature is the large, chaotic fluctuations in the density caused by convective motions in the disk. SOURCE: J. Stone, Princeton University.

explode as supernovae requires three-dimensional computations similar to those used to study fuel efficiency in cars and the design of new rockets but in far more exotic and challenging conditions (Figure 5.5).

Finally, understanding planet formation, an issue central to the Panel on Planetary Systems and Star Formation, is one of the most challenging tasks in astrophysics. A comprehensive theory of planet formation requires following the growth of dust grains in the protoplanetary disk into small rocky bodies, the growth of these bodies into planets, and the subsequent development of oceans and atmospheres—a study spanning some 42 orders of magnitude in mass and a vast array of processes ranging from the sticking properties of dust grains, through the dynamics of bodies in shearing gas flows, to gravitational stability of planetary orbits on billion-year timescales.

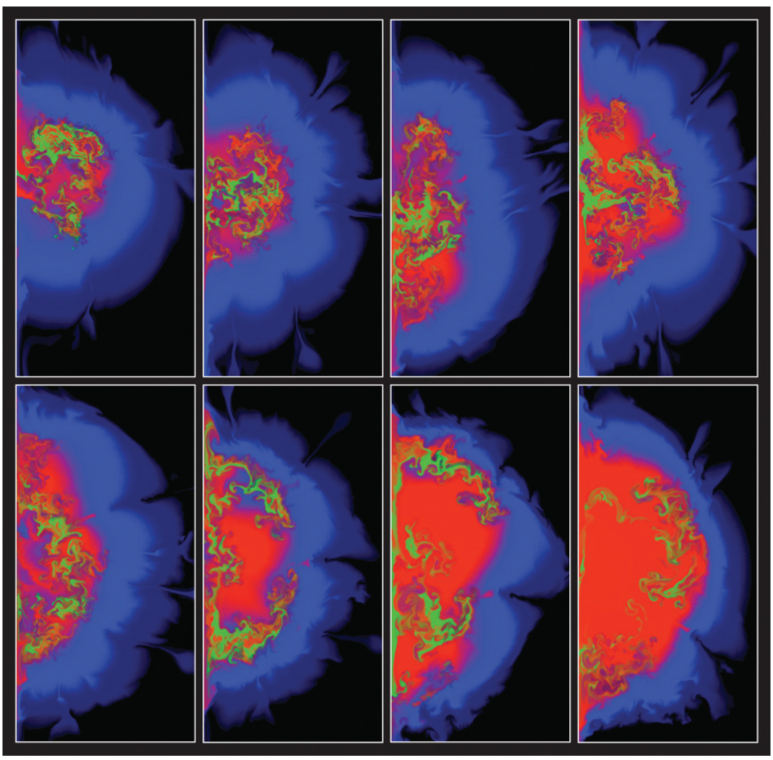

FIGURE 5.5 Theoretically predicted chemical structure 100 seconds after the explosion of a massive carbon/oxygen white dwarf. The blue regions show intermediate-mass elements (e.g., silicon, sulphur, calcium), green indicates radioactively stable iron-group elements, and red indicates ^{56}Ni, the isotope that powers the supernovae for the next few months. SOURCE: Reprinted by permission from Macmillan Publishers Ltd: Nature, D. Kasen, F.K. Röpke, and S.E. Woosley, The diversity of type Ia supernovae from broken symmetries, Nature 460:869-872, 2009. Copyright 2009.

Individual Investigator Programs in Theory and Computation

Astrophysical theory is intellectually vibrant, and productivity is high: about 45 percent of published papers are on theory, and about one-third of publishing astronomers are pursuing theory (see Figure 4.9). Based on the recent record, there is a compelling case that investments in theory by the agencies will be amply repaid in the form of new mission and experiment concepts and enhanced scientific return from operating facilities. Astrophysical theory draws some of the world's best intellectual talent into the U.S. scientific enterprise. Because some of the most important theory contributions in the next decade will come from broadly based theory not specifically tied to large activities, the role of general individual investigator programs will continue to be as important as ever. These programs form the traditional base of theoretical astrophysics in which Ph.D. students are trained, new ideas arise, and future observational or experimental efforts are seeded.

Astrophysics and cosmology theory is supported through a number of programs at the federal agencies. At NSF, general astrophysics theory is funded through the AST Astronomy and Astrophysics Research Grants (AAG) program,[5] as well as through the NSF Division of Physics (NSF-PHY) via its Frontier Centers and individual investigator grants in cosmology and particle physics theory. At NASA, the Astrophysics Theory Program (ATP) supports most general theory efforts. In addition, the Hubble, Spitzer, Chandra, and Fermi Observatories accept theoretical investigations as part of their guest investigator programs. Other critical support comes from NASA Prize Postdoctoral Fellowship programs (Einstein, Hubble, Sagan). The DOE's Office of High Energy Physics also supports theoretical and computational astrophysics efforts. Table 5.2 summarizes current funding levels.

As is the case with the grants programs in general, proposal success rates in theory have declined over the past decade. The recent success rate in NASA's ATP is only 15 to 20 percent, significantly lower than funding rates for theory within its Planetary Exploration program, for example. Given the central importance of theory to the enterprise, and the crucial role played by individual investigator grants, the committee recommends in Chapter 7 that the grants programs at both NSF and NASA be augmented.

The Rapid Rise of Astrophysical Computing

The dramatic impact of computation on astronomy and astrophysics is manifested in many ways. Modern numerical codes are now being used to simulate and

[5] The financial support for theory within the NSF-AST AAG program is roughly 7 percent of the total NSF-AST budget and, for comparison, about 10 percent of both the NSF-PHY and DOE Particle Astrophysics budgets.

TABLE 5.2 Support for Astrophysics and Cosmology Theory

Program	Budget (million $)
NSF-AST Astronomy and Astrophysics Research Grants	15.1
NSF other (AAPF, CAREER, Cyberinfrastructure, and others)	5.3
NSF-PHY Astrophysics and Cosmology Theory	1.2
NSF-PHY Physics Frontier Centers	(several)
NASA Astrophysics Division Astrophysics Theory Program	12.4
NASA Astrophysics Division Great Observatories Guest Observer Programs	2.2
DOE Scientific Discovery through Advanced Computing	0.7
DOE High Energy Physics Theory	10
DOE Nuclear Physics Theory	3

understand the formation of structure in the universe, the explosion of massive stars, the evolution of our solar system over billions or trillions of years, and how a complex experiment works. They are also essential to processing astronomical images whose sizes now exceed 1 billion bytes (a gigabyte) into data that are usable by the astronomical community. The largest codes may have in excess of a million lines and run on supercomputers that have more than 100,000 cores, generating data sets that occupy 1 trillion bytes (a terabyte) of storage. These codes are now an indispensible part of the astronomical enterprise. However, they often require teams—scientists, computer professionals, applied mathematicians, and algorithm specialists—to create, maintain, and constantly develop them.

NSF, NASA, and DOE have made substantial investments in high-performance computing (HPC) over the past decade, making available close to a petaflop of sustained computing power to the astrophysics community. Such facilities enable cutting-edge theoretical calculations and analyses that push the astrophysics frontier. Future progress in supercomputer power will come from further parallelization, with the largest systems evolving from 10^4 to 10^5 processor cores today to perhaps 10^8 to 10^9 cores by the end of the decade.[6]

These capabilities will enable qualitatively new physical modeling.[7] Exploiting the new computer systems will require new software codes and sustained support for focused research groups. At the same time, strategic balance should be maintained between investment in HPC and hardware resources for individual investi-

[6] Such large increases in processing capability carry implications for the amount of power and cooling that will be necessary. On the presumption that the total power usage cannot increase significantly in a "green" computing future, major advances in chip design and special-purpose software will be necessary.

[7] Simulations in cosmological structure formation, galaxy formation, stellar evolution, supernova explosions, gamma-ray bursts, star formation, planet formation, and high-energy particle acceleration are just a few example areas.

gators and university-department-scale clusters, which are critical for exploratory and smaller-scale projects and for the training of students.

Research Networks in Theoretical and Computational Astrophysics

A large number of the theoretical challenges posed by the Science Frontiers Panels are of a scale and complexity that require sustained, multi-institutional collaborations of theorists, computational astrophysicists, observers, and experimenters. There is currently no mechanism to support these coordinated efforts at the required level in the United States; however, successful models for such coordinated efforts exist in Europe.[8] Opportunities used to exist for such medium-scale group efforts in the NASA ATP, but more recently ATP has been focused on individuals and small single-institution groups. Appropriately focused and led research collaborations and networks are "efforts of scale" that can make long-term investments in personnel, computing, and scientific networking uniquely effective in tackling some of the most difficult problems in modern astrophysics.

RECOMMENDATION: A new program of Research Networks in Theoretical and Computational Astrophysics as discussed in Chapter 7 should be funded by DOE, NASA, and NSF. The program would support research in six to eight focus areas that cover major theoretical questions raised by the survey Science Frontiers Panels.

The networks would be devoted to a specific problem or topic that is believed to be ripe for a breakthrough within 5 years. Selection criteria would include the degree of cross-institutional synergy in the network and its planned role in training and mentoring the next generation of researchers. Funding would normally be for a 5-year period, and the entire program would be subject to a senior review after 5 years. These networks fulfill a role different from that of NASA's ATP and NSF's AAG program and should not be funded at their expense. For NSF's AAG program the success rate for theory proposals is roughly 37 percent.

DATA AND SOFTWARE

The scientific richness and extent of astronomical data sets are increasing rapidly. The sizes of modern databases have grown over the past decade into

[8] As an example, the Deutsche Forschungsgemeinschaft (the German Research Foundation) has established "Priority Programs" that enable large coordinated theory efforts. An example of a recently established Priority Program is "Witnesses of Cosmic History: Formation and Evolution of Black Holes, Galaxies, and Their Environment."

the petabyte (1 million gigabytes) range, with a current growth rate of roughly 0.2 petabytes per year. Challenges for data archiving will increase dramatically in the future. The committee's top-ranked ground project, the Large Synoptic Survey Telescope (LSST), expects its archive to grow by a petabyte per month. A complete SKA operated in the manner of the VLA or ALMA would operate in the thousand-petaflop, or exaflop (1,000 petaflops), scale compared with the petaflop of sustained power consumed by current astronomical computing. Proper maintenance and accessibility of these archives are essential to optimizing scientific return, especially for LSST studies of transient and time-variable phenomena for which rapid availability of validated data will be critical.

As discussed in Chapter 3, the AAAC can play a key role in providing tactical advice to DOE, NASA, and NSF on the support of data archiving and dissemination, and on data analysis software funding across the three agencies relative to the agencies' programmatic needs as identified by Astro2010. In particular, the optimal infrastructure for the curation of archival space- and ground-based data from federally supported missions and facilities will need periodic attention.

Data Archives

Data archives are central to astronomy today, and their importance continues to grow. The science impact of these archives is large and increasing rapidly. Papers based on archival data from the Hubble Space Telescope now outnumber those based on new observations in any year and include some of the highest-impact science from the HST, as shown in Figures 5.6 and 5.7. Data from the 2 Micron All Sky Survey (2MASS) and the Sloan Digital Sky Survey (SDSS), which were both designed as archival projects, led to more than 1,400 and 2,650 refereed papers in the past decade, respectively, with the scientific output continuing to increase well after the completion of these surveys.

Publicly accessible data archives can multiply the scientific impact of a facility or mission—for a fraction of the capital and operating costs of those facilities or missions. The data explosion and the long-term need for the ability to cross-correlate enormous data sets require archival data preservation beyond the life of projects and the development of new analysis and data-mining tools. The establishment over the past decade of the National Virtual Observatory, a top recommendation of the 2001 decadal survey and part of an International Virtual Observatory initiative, has produced widely accepted standards for data formatting, curation, and the infrastructure of a common user interface. These standards have the potential to substantially enhance the collective value of archival data sets.

NASA has regarded data handling and archiving as an integral part of space missions. It has established a network of data centers to host data from NASA mis-

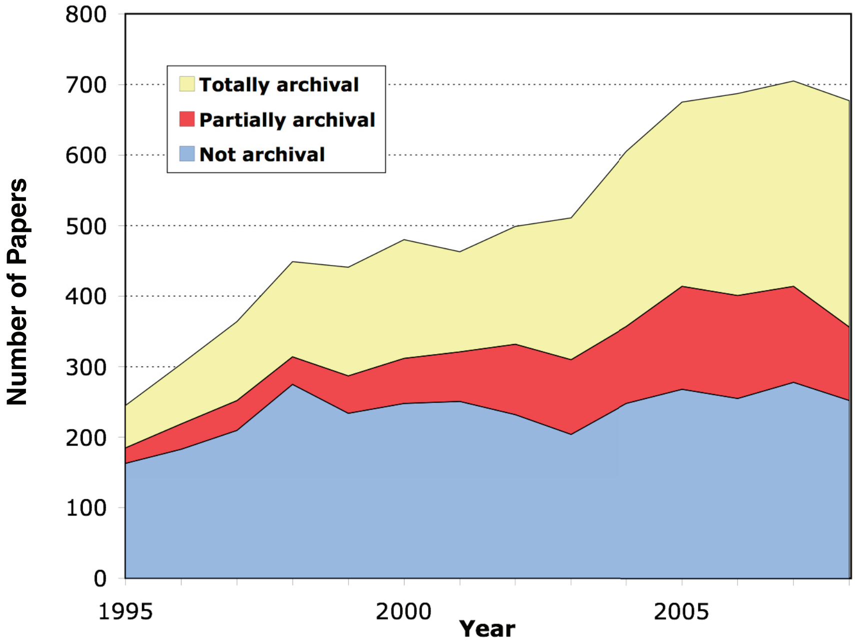

FIGURE 5.6 Number of published papers using Hubble Space Telescope data, 1995 to 2008. The publications are divided into non-archival papers written by the original investigators (blue), fully archival publications not involving any of the original investigators (yellow), and papers, some archival and some not, that include data from multiple proposals (red). The number of archival papers has exceeded the number of original-investigator-written papers since 2006. SOURCE: Courtesy of Richard L. White, Space Telescope Science Institute.

sions, and a National Research Council report[9] lauded their efficiency. This support now provides the major return on the considerable investments the agency has made in the Great Observatories and other facilities over the past 20 years. The 2007 report also found that the consolidation of archives at a small number of facilities is efficient, cost-effective, and serves the scientific community well.

[9] The 2007 National Research Council report *Portals to the Universe: The NASA Astronomy Science Centers* (The National Academies Press, Washington, D.C.) emphasizes the role of NASA archives in allowing astronomers to examine data on a particular target set across a range of wavelengths: "Not only are the archives the keepers of the raw observations, but they also provide direct access to calibrated versions of their data products, with online documentation and searchable databases linked to the literature. This 'shrink-wrapped' feature of modern archives makes it easier for astronomers to combine data across various subdisciplines, a task that would have been difficult even a few years ago when all astronomers had their own sets of tools and did most of the data reduction themselves" (p. 25).

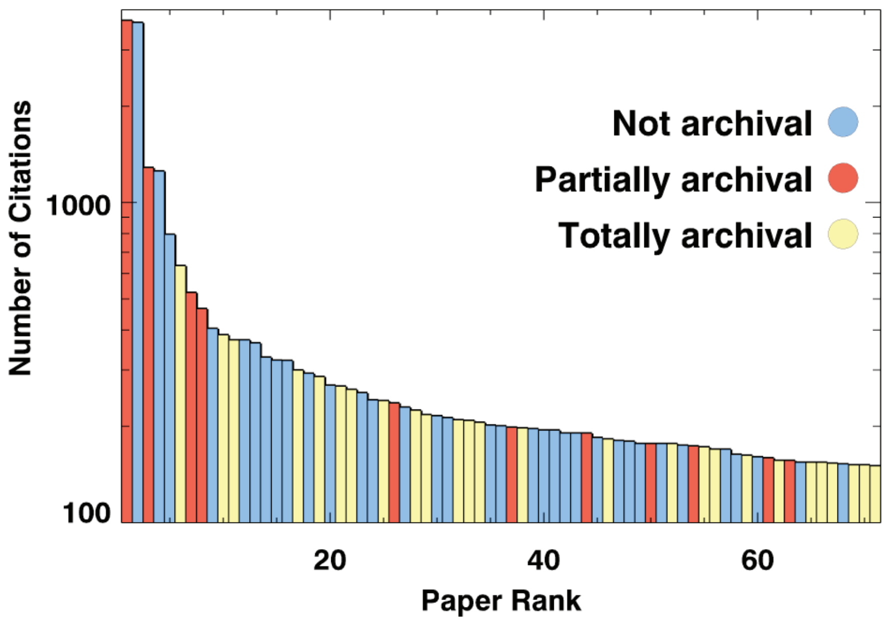

FIGURE 5.7 Highly cited Hubble Space Telescope publications, 1997 to 2000. All 71 papers with more than 150 citations as of March 2009 are included in the sample. Note that the y-axis is logarithmic. Totally archival papers make up 37 percent of the sample. SOURCE: Courtesy of Richard L. White, Space Telescope Science Institute.

On the ground, major surveys, such as 2MASS and SDSS in the optical-infrared, the FIRST and NVSS radio continuum surveys, and the ALFA H I (neutral hydrogen) and pulsar surveys, had archives built into their programs. Radio interferometers generally have standardized observing protocols that make it straightforward to archive the data taken. Radio telescopes operating as single apertures and ground-based optical-infrared telescope user facilities have, in large measure with the exception of the Gemini Observatory, not yet developed an archiving culture, although most major facilities do "save the bits" of raw data. Partly, this lack of an archiving culture is due to the difficulty and consequent cost of archiving data taken under a multiplicity of observing modes. Although cost-benefit considerations must be weighed, given the current trends in the demand for archived data and the growth of private-public telescope partnerships, the committee finds it highly desirable for ground-based telescopes to make data archiving an integral part of their operations in the future.

Archives of either raw or processed data should contain complete calibration information, a history of data processing and/or the software to process the data, and access to tools to analyze the data. The format should be Virtual

Observatory-compliant when this is cost-effective. Astronomical librarians and data archivists should be involved in metadata design and curation. While NASA has an established policy whereby archiving and public access are required and costs are included in mission budgets, NSF has no consistent policy. Financial support made available under agency peer-review processes would enable existing observatories to implement such archives. DOE has a culture that supports modern data handling and prudent selection of which data to archive. It does not have a culture of public access but has adapted well to such practice in its collaborations with astrophysicists.

RECOMMENDATION: Proposals for new major ground-based facilities and instruments with significant federal funding should be required as a matter of agency policy to include a plan and if necessary a budget for ensuring appropriate data acquisition, processing, archiving, and public access after a suitable proprietary period.

To be practical and cost-effective, this requirement should be limited to data that are reasonably likely to be of interest to other users, for example large survey programs and other significant principal-investigator-led efforts in optical-infrared and radio astronomy. The committee further concluded that public funds could support public archiving of data from facilities that are fully funded from private sources, should such support be proposed and highly reviewed. Proposals to NSF's Astronomy and Astrophysics Research Grants program or to the ATI program could include support for the development of software tools related to data reduction and analysis, and archiving.

Because data archives are so central to modern astronomy, it is a matter of concern that no model exists for long-term preservation (curation) of ground-based data once observing projects or facilities are no longer funded.[10] To realize the full benefit of ground-based data, especially from surveys, it is therefore necessary for NSF to adopt the model of NASA's long-lived data archive centers (like IPAC, MAST, HEASARC) and also of the Canadian Astronomy Data Center for long-term curation of data, with capabilities similar to those available through existing successful archives.

A coordinated interagency effort will be particularly important with the advent of the petabyte-scale surveys anticipated in the future. An example of an opportunity for possible synergy in combining ground-based and space data is solar physics. The rapidly growing database from existing facilities including the Solar Dynamics Observatory presents an opportunity to combine complementary data sets in order to obtain a balanced view of the dynamic Sun. This investment

[10] An exception is the 2MASS survey, which resides within the InfraRed Science Archive at IPAC.

is likely to pay a large dividend when the Advanced Technology Solar Telescope comes on line in 2017. The National Science Board report *Long-Lived Digital Data Collections: Enabling Research and Education in the 21st Century*[11] and the National Academies report *Ensuring the Integrity, Accessibility, and Stewardship of Research Data in the Digital Age*[12] both recognized the growing importance of long-term curation, and the NSB report recommended that NSF develop a global strategy to address it. The NSF Office of Cyberinfrastructure's DataNet program (Sustainable Digital Data Preservation and Access Network Partners), which is partnering with research institutions to develop data preservation facilities of general utility to the research community and which includes participation by astronomers, is an important first step in the process.

RECOMMENDATION: NSF, NASA, and DOE should plan for effective long-term curation of, and access to, large astronomical data sets after completion of the missions or projects that produced these data, given the likely future scientific benefit of the data. NASA currently supports widely used curated data archives, and similar data curation models could be adopted by NSF and DOE.

The committee estimated the cost of achieving these data-archiving goals on the basis of an informal survey of existing archives. Data gathered by the survey's Infrastructure Study Groups indicate that adding the data from a new survey similar to SDSS to the portfolio of an existing archive center would involve startup costs of about $0.4 million (approximately $0.15 million for personnel and $0.25 million for hardware) and an annual operating budget of about $0.2 million to $0.3 million ($0.15 million for personnel and the remainder for maintenance and upgrades). Starting a new archive from scratch would be significantly more expensive, and so it would be particularly cost-effective for NSF and DOE to coordinate with NASA to use existing archive and data distribution centers. An added scientific advantage would be having a core of resident astronomers, computer scientists, and technical support staff.[13] Supporting additional archiving and long-term curation for a few existing observatories and instruments would cost roughly $15 million per decade. Numerical codes could also be curated.

[11] National Science Board, *Long-Lived Digital Data Collections: Enabling Research and Education in the 21st Century,* NSB-05-40, National Science Foundation, Arlington, Va.

[12] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Ensuring the Integrity, Accessibility, and Stewardship of Research Data in the Digital Age,* The National Academies Press, Washington, D.C., 2009.

[13] National Research Council, *Portals to the Universe,* 2007.

Data Reduction and Analysis Software

Major instruments with wide public use on federally supported telescopes and facilities would benefit greatly from pipelines that deliver calibrated data and data products for storage in a public archive. General-purpose community analysis software packages like the Image Reduction and Analysis Facility and Astronomical Image Processing System currently used by optical and radio astronomers are more than 30 years old and will not be able to handle future needs. In addition, specialized programs for automated data-handling tasks across many areas of astronomy and astrophysics must be written. New packages capable of handling large data sets are urgently needed. These are likely to be created and employed within a common-use environment. Flexibility, openness, and platform independence, modularity, and public dissemination are essential to this effort. Focused investment in a series of small-scale initiatives for common tool development and the collection of those tools in a public portal may be the most cost-effective approach, although there are undoubtedly synergies with the pipeline development needed for the large-scale projects. Further, central data archives, in which the survey committee recommendeds all future major projects participate, could maintain current software versions and provide community access and documentation for general data reduction tools.

MEDIUM-SCALE ACTIVITIES

A major recommendation of this report, directed to both the ground and the space programs, is that more support should be directed toward activities of intermediate scale. For the space program, both NASA's Explorer program and its Suborbital program are recommended in Chapter 7 for funding increments. For the ground-based program, the committee endorses the recommendations of several previous advisory groups to NSF that there be mid-scale funding opportunities, and it recommends in Chapter 7 a new competed program. Medium-scale programs and experiments offer excellent return for the investment and are essential to the capability for responding flexibly to new scientific opportunities, for demonstrating novel techniques and instruments, and for training the experimental scientists, engineers, and managers who will execute the major missions and observatories of tomorrow.

Technical Workforce Development

The designers of missions and telescopes, and those who implement instruments and understand their performance, are central to the astrophysics enterprise. One of the most important elements for reducing technical and schedule risk for any space mission or major ground-based project is a highly experienced team.

The current distribution of activities and grants funding poses particular challenges for maintaining a workforce skilled in instrument and project development. Although properly funded programs for space and ground facilities often provide significant support for the training of new data analysts, the opportunities for training students in instrumentation have declined precipitously over the past 20 years. Training for the next generation of instrumentalists is most efficient when there is a steady-state hierarchy of project sizes, so that people can progress from relatively smaller, simpler, and faster projects to responsibilities in larger and more complex activities.

Despite existing NASA and NSF funding mechanisms that can support technology training, the data gathered by the survey's Infrastructure Study Groups show that fewer than 5 percent of students recently receiving Ph.D.s from astronomy departments classify themselves as belonging to "instrumentation and methods" subfields. If there are to be enough young instrumentalists to spearhead the ambitious new instruments and facilities of the coming decade, more must be done within graduate astronomy programs to educate and train them. The growth of astrophysics research within physics departments can help in this regard.

Some of the input Astro2010 received in white papers submitted by the community discussed the need for increased emphasis on instrumentation within U.S. astronomy and astrophysics Ph.D. programs. It is important that universities recognize the value of skilled instrumentalists, and that they continue to provide opportunities for early-career training. Further, the scientific community must value the intellectual contributions of instrumentalists as an integral part of the astrophysics endeavor.

NASA Explorer and Suborbital Programs

The Explorer program, which develops small and mid-size missions on timescales of a few years, is a crown jewel of NASA space science. Its tremendous scientific productivity results from the selection and implementation of focused scientific investigations enabling rapid response to new discoveries. For example, among the astrophysics Explorers, the WMAP Medium-scale Explorer (MIDEX) mission capitalized on the discovery made by a previous Explorer, COBE, that the microwave background has measurable fluctuations. Launched just 5 years after the COBE results were published, WMAP demonstrated that precise information about the early universe is imprinted on these minute fluctuations, leading to greater understanding of the age, geometry, and content of the universe; the papers based on WMAP data are the among the most highly cited in all of astrophysics. The Swift gamma-ray burst (GRB) MIDEX was launched just 7 years after the discovery that GRBs—bright, few-seconds-long, high-energy pulses from the cosmos—are accompanied by long-lived afterglows extending down to radio wavelengths. These afterglows enable us to associate GRBs with the birth cries of black holes from across the universe. Swift's success was rewarded when it was identified as the highest-ranked mission in the 2007 senior review—a process that compared its scientific returns to those of major flagship missions. The GALEX Small Explorer (SMEX) ultraviolet mission is changing our understanding of how stars formed and how galaxies evolved over the past 10 billion years of cosmic history, and it is now supporting an active guest investigator program. The recently launched WISE MIDEX is successfully conducting an all-sky mid-infrared survey with announced discoveries ranging from asteroids and comets to active galactic nuclei.

In addition to these stand-alone experiments, the Explorer program supports Missions of Opportunity (MoOs)—contributions of instruments or investigations to space programs led by other countries. MoOs provide highly leveraged mechanisms to broaden the astrophysics program, deploy new technologies, and return significant science for relatively modest investments. In addition, suborbital science experiments can be proposed as MoOs.[14]

NASA's suborbital (balloon and rocket) programs enable scientific experiments with equipment ranging from particle detectors to X-ray, gamma-ray, infrared, and microwave instruments. They support substantive scientific investigations in areas such as CMB and particle astrophysics, fulfill essential needs in technology development, and provide invaluable hands-on training. Notably, key positions in mission development across NASA are occupied by people who received their training through participation in suborbital missions. This group is aging, however, and replacements are few (Figure 5.8). Although NASA maintains a technical workforce within its stably funded centers, the groups in universities that train students to renew NASA's talent are subject to large variations in funding associated with individual missions. As a result of diminishing astrophysics budgets combined with full-cost accounting, the NASA centers are also now competing for the smaller training projects that used to be located across multiple universities.[15] In light of identified exceptional science opportunities now and ahead, there is a clear need to renew the talent pool of experienced instrumentalists, and the committee makes a number of related recommendations in this report. In Chapter 7, the committee recommends increased support for the Suborbital program, as well as an augmentation to the Explorer program that will double the number of opportunities for stand-alone missions and vastly increase the number of Missions of Opportunity. Historically, Explorer missions and suborbital experiments have

[14] National Research Council, *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce,* The National Academies Press, Washington, D.C., 2010. Available at http://www.nap.edu/catalog.php?record_id=12862. Accessed May 2010.

[15] See the 2010 National Research Council report *Capabilities for the Future: An Assessment of NASA Laboratories for Basic Research,* The National Academies Press, Washington, D.C. Available at http://www.nap.edu/catalog.php?record_id=12903.

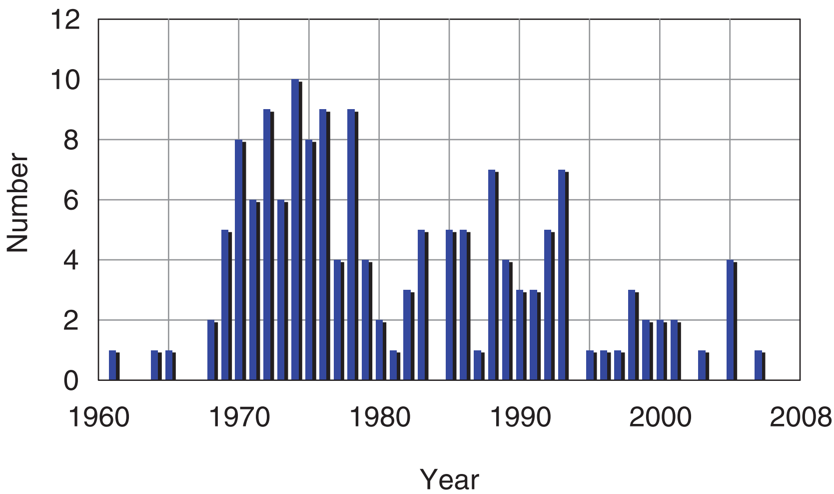

FIGURE 5.8 Number of Ph.D.s awarded per year to individuals trained in sounding rocket programs, 1961 to 2008. SOURCE: NASA Astrophysics Sounding Rocket Assessment Team.

included significant instrumentation efforts centered at universities, and their development timescales are suitably short, compared with those of flagship missions, so as to match graduate student and postdoctoral fellow terms of study.

NSF Mid-Scale Innovation Program

The cost of major new instruments and facilities has increased significantly over the past 20 years, to some extent reflecting increasing scale and complexity. For example, instruments for 8- to 10-meter-class ground-based telescopes are necessarily larger and hence more costly than those for smaller telescopes. Similarly, large focal plane arrays for radio telescopes are more costly than the previous generation of non-multiplexed receivers. In addition, providing a significant enhancement over current capabilities requires applying new and more expensive technology such as adaptive optics systems in the optical or complex correlator systems in the radio. Finally, as data output increases to many terabytes, data management and software complexity add to instrument and facility costs.

Within NSF, grants programs such as Astronomy and Astrophysics Research Grants, Advanced Technologies and Instrumentation, and Major Research Instrumentation provide funding for training young people in instrumentation and telescope design, data analysis, and data interpretation, and such training has been funded relatively steadily over the past decade (Table 5.3). NSF grants typically involve a graduate student or postdoctoral fellow who is learning about instrumen-

TABLE 5.3 Detailed NSF-AST Non-facilities Budgets (in millions of FY2010 dollars)

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
R&E	**34.21**	**42.19**	**44.77**	**57.68**	**62.04**	**61.02**	**60.60**	**61.92**	**63.91**	**64.53**
AAG	24.09	26.11	27.73	35.36	38.11	35.23	35.55	41.80	43.61	43.03
ESP	6.19	6.05	6.20	6.55	6.25	6.15	5.81	5.94	5.70	6.87
AAPF	0.00	0.00	0.73	1.44	1.69	1.78	1.79	1.63	1.58	1.41
ESM	0.13	0.26	0.20	0.13	0.21	0.30	0.22	0.22	0.21	0.19
STC	0.88	8.21	2.10	4.84	4.71	4.51	4.44	4.30	4.21	3.39
Projects	0.00	0.00	0.00	0.89	0.47	1.32	4.01	1.30	1.49	2.59
Initiatives	2.11	1.25	7.08	7.69	9.92	11.13	7.97	5.68	5.79	5.31
Panels/IPAs	0.81	0.32	0.72	0.77	0.68	0.60	0.80	1.05	1.32	1.74
Inst/Tech	**8.92**	**9.36**	**10.23**	**16.29**	**22.36**	**22.42**	**23.79**	**21.63**	**31.57**	**30.01**
ATI[a]	7.99	8.22	8.01	9.75	12.18	10.79	10.51	8.44	10.28	9.22
CIP	0.00	0.00	0.61	4.81	8.17	9.11	4.66	5.23	6.85	4.09
Tech/MSP	0.93	1.14	1.61	1.73	2.01	2.52	8.62	7.96	14.43	16.70
TOTAL	43.13	51.55	55.00	73.97	84.41	83.44	84.38	83.55	95.48	94.54

NOTE: AAG, Astronomy and Astrophysics Research Grants; AAPF, Astronomy and Astrophysics Postdoctoral Fellows; ATI, Advanced Technologies and Instrumentation; CIP, Community Instrumentation Programs (TSIP, AODP, PREST); ESM, Electromagnetic Spectrum Management; ESP, Education and Special Programs; Initiatives, AST funding to NSF- or MPS-wide programs; Inst/Tech, Instrumentation and Technology Development programs; Panels/IPAs, Review panels and Intergovernmental Personnel Act appointments; Projects, Special Projects; R&E, Research and Education programs; STC, Science and Technology Centers; Tech/MSP, Technology development and mid-scale projects.

[a] NSF's ATI program fluctuated by only about 15 percent in FY2010 dollars over the decade 1999 to 2008.

SOURCE: NSF Division of Astronomical Sciences.

tation, and the ~3-year grant duration is long enough to cover much, but frequently not all, of a graduate student's Ph.D.-thesis years. The Telescope System Instrument Program and the University Radio Observatory program, described in Chapter 6, help provide the facilities for students to learn observing procedures and develop new instrumentation. In Chapter 7 the committee recommends augmentations for several of these programs. However, some of the most compelling science opportunities and instrumentation frontiers—and therefore the areas of highest interest among young people—are beyond the scales of even the largest of these mid-scale programs.

A National Science Board report[16] and a National Research Council report[17] both emphasized that NSF should address the need for mid-size infrastructure, as have the NSF Division of Astronomical Sciences (NSF-AST) senior review,[18] several AAAC annual reports,[19] and multiple Committees of Visitors to NSF-AST, NSF-PHY, and the NSF Division of Materials Research of its Directorate for Mathematical and Physical Sciences (MPS) between 2003 and 2009. All of these reports stated that NSF needs a better mechanism to fund projects with costs between the top of the MRI funding bracket ($4 million to $6 million varying over the decade) and the bottom of the MREFC funding bracket (~$135 million).

Since at least FY2007, mid-scale instrumentation has been identified as a priority of NSF's MPS directorate. In FY2009 and FY2010 mid-scale instrumentation was called out as a priority for NSF-AST, with increases resulting in expenditures of $32 million in FY2010. Beyond spending on GSMT, LSST, and SKA technology, design, and development, the projects funded include SDSS-II and SDSS-III, VERITAS, the Murchison Widefield Array, the Atacama Cosmology Telescope, PolarBeaR, and QUIET. Some of these were co-funded by NSF-PHY.

In Chapter 7, the committee recommends the establishment of a formally competed mid-scale instrumentation and facilities line within NSF-AST with additional funding beyond that currently being provided. The program would be focused specifically on the construction costs of instruments and facilities that fall between the top of the MRI and the bottom of the MREFC funding ranges. This survey received 29 proposals that would be eligible for such a competition, many of which were highly rated by the survey's Program Prioritization Panels (PPPs) because they address directly the frontier science questions identified by the SFPs.

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[16] National Science Board, *Science and Engineering Infrastructure for the 21st Century: The Role of the National Science Foundation,* NSB 02190, National Science Foundation, Arlington, Va., 2003.

[17] National Research Council, *Advanced Research Instrumentation and Facilities,* The National Academies Press, Washington, D.C., 2006.

[18] National Science Foundation, *From the Ground Up: Balancing the NSF Astronomy Program,* Report of the NSF Division of Astronomical Sciences Senior Review Committee, National Science Foundation, Arlington, Va., 2006.

[19] Astronomy and Astrophysics Advisory Committee, *Annual Report 2007* and *Annual Report 2008*, available at http://www.nsf.gov/mps/ast/aaac.jsp.

TECHNOLOGY DEVELOPMENT

Technology development is the engine powering advances in astronomy and astrophysics, from vastly extending the scientific reach of existing facilities to opening up new windows on the universe. All of the Astro2010 PPPs emphasized the critical importance of technology development, and each stressed the urgent need to augment existing funding levels to realize important programs essential to reducing the technical, cost, and schedule risk of planned missions. Mission- or project-specific technology development must reach an acceptable level before accurate costs can be determined, priorities set, and construction scheduled. Failure to develop adequately mature technology prior to a program start also leads to cost and schedule overruns.

NASA-Funded Space-Based Astrophysics Technology Development

Technology development in three categories is discussed in this section:

1. Near-term mission-specific technology development is directed toward the particular requirements of a specific mission.
2. Mid-term or "general" technology development is aimed at maturing the technical building blocks (detectors, optics, and so on) that will enable high-priority science to be done on future missions with low risk and predictable cost.
3. Long-term or "blue sky" development supports novel ideas and approaches that could lead to transformational improvements in capability and enable missions not yet dreamed of—a level of technology development that is crucial to the future vitality of NASA.

Near-Term Mission-Specific Technology Development Needs

Ensuring adequate funding up front for mission-specific technology development is critical to predicting and managing mission costs and schedules.[20] It has been reported that "in the mid-1980s, NASA's budget office found that during the first 30 years of the civil space program, no project enjoyed less than a 40 percent cost overrun unless it was preceded by an investment in studies and technology of at least 5 to 10 percent of the actual project budget that eventually occurred."[21]

[20] Such technology development was also recommended in a 2009 NRC report, *America's Future in Space: Aligning the Civil Space Program with National Needs*, The National Academies Press, Washington, D.C. Available at http://www.nap.edu/catalog.php?record_id=12701.

[21] John C. Mankins, The critical role of advanced technology investments in preventing spaceflight program cost overrun, *The Space Review*, December 1, 2008. Available at http://www.thespacereview.com/article/1262/1. Accessed May 2010.

Mission-specific technology development funding has suffered substantial cuts over the past decade, cuts reflected in the immature state of a number of missions the survey committee has ranked as having very high scientific priority. The Astro2010 Panel on Particle Astrophysics and Gravitation found that further investment is needed in systems engineering and life-testing of components for the LISA Pathfinder mission, which is designed to demonstrate a number of LISA's critical technologies. The Panel on Electromagnetic Observations from Space identified significant technology development needs for IXO, primary among them being the selection and demonstration of the critical X-ray optics. The survey committee also found IXO technologies to be too immature at present for accurate cost and risk assessment, and therefore recommends (in Chapter 7) significant investment in technology development during this decade so that IXO can be considered ready for a mission start early in the next decade. Instrumentation for the SPICA mission is a third area where specific technology development funds are needed during this decade. Determining the optimum funding levels is difficult, but NASA should collect and analyze the appropriate statistical data and apply sufficient funds for technology maturation for LISA, IXO, and SPICA.

Mid-Term Technology Development

Mid-term technology development enables defining, maturing, and ultimately selecting approaches to realize future scientific goals. In mid-term technology development it is usually necessary to pursue multiple paths to the same end, since both the detailed science requirements and the success of particular technologies remain uncertain. In addition, it is essential to pursue a broad range of technologies spanning the electromagnetic spectrum to ensure the vitality of competed mission lines and to pave the way for next-decade missions. The later stages of mid-term development are typically more costly than early-stage concept demonstration, because they may involve expensive prototypes or significant engineering efforts to design systems that can withstand testing in relevant environments.

The committee identified a number of high-priority science areas for which mid-term investments are needed beginning early in the decade, including development of a variety of technologies for exoplanet imaging, such as coronagraphs, interferometers, and star shades, leading to possible late-decade down-selecting. In addition, mid-term investment is needed for systems aimed at detecting the polarization of the CMB, and for optics and detectors for a future space UV space telescope. Broad-based mid-term technology development is also crucial to the Explorer program, which selects missions that can be implemented on short timescales.

Mid-term technology development is funded primarily through NASA's Astronomy and Physics Research and Analysis (APRA) program, which was cut considerably in the middle of the past decade. Although APRA funding has been restored to approximately 80 percent of its 2004 level (in FY2010 dollars), specific science priorities identified by the committee and its Program Prioritization Panels led the committee to recommend establishing these mid-term technology development programs and restoring APRA funding to a level matched to the needs of long-term technology development as described below. In Chapter 7 the committee recommends specific technology development programs in exoplanet, CMB, and UV instrumentation, as well as an augmentation to general mid-term development efforts that would ramp up by the end of the decade. Suborbital programs (balloons and rockets),which demonstrate scientific potential and test technologies in a space environment, are also critical in mid-term technology development and also are recommended in Chapter 7 for an augmentation.

Long-Term Technology Development

Long-term technology development builds the future of the space astrophysics program. It has become standard to achieve order-of-magnitude or greater increases in capability with each generation of missions, and exciting science breakthroughs have been achieved as a result. The only way to advance to the next capability without an exponential increase in mission costs is to find transformational new technological solutions. Some of the breakthroughs and advances have come from outside (such as microelectronics and near-IR detector arrays), but many of the technologies required in astrophysics are unique to the field, and their development must be supported from within. Examples of truly revolutionary technologies, essential to existing and upcoming astrophysics missions, that have been largely or entirely supported by NASA are X-ray imaging mirrors, X-ray microcalorimeters, and large arrays of submillimeter detectors. Future needs might include atomic laser gyros for pointing an X-ray interferometer, lightweight active mirror surfaces, new grating geometries, and novel techniques for nulling interferometry.

The appropriate level of investment in technology of long-term benefit is difficult to determine. A recent NRC report provides an excellent discussion of the metrics that should be used to establish and maintain a balanced technology development program but does not attempt to specify appropriate funding levels.[22] It points out the clear importance of the long-range, high-risk, high-payoff component of technology development, noting that industry typically devotes 5 to 10 percent of R&D budgets to this component. Another report, which concluded that about 8 percent of a government entity's research budget should be set aside for

[22] National Research Council, *An Enabling Foundation for NASA's Space and Earth Science Missions,* The National Academies Press, Washington, D.C., 2010.

high-risk research,[23] also emphasized the difficulty of managing this type of development: when resources are limited, the temptation is always to cut long-range work in order to satisfy the more immediate demands of near-term technology requirements. Keeping the funding steady and healthy for promising long-term work while carefully evaluating it to avoid waste requires considerable attention from long-term program managers. An NRC recommendation to NASA was that the agency increase the number of scientifically and technically capable program officers, so that they could devote an appropriate level of attention to the tasks of actively managing the portfolio of research and technology development that enables a world-class space science program.[24]

Long-term technology development is funded at small levels from the APRA program. In the past, the Research and Engineering Directorate funded long-term and cross-cutting technologies (i.e., technologies with broad application within NASA), but this program was discontinued in the past decade. The committee was pleased to learn that NASA is planning to re-invigorate technology development across the enterprise, and it hopes that this effort will be managed in a way that provides an increased variety of opportunities for far-sighted work toward the future needs of astrophysics.

To address the issues raised above concerning support of mid-range technology development for future astrophysics missions, the committee recommends in Chapter 7 increases in the funding levels of NASA's APRA and Suborbital programs. The adequate support of technology development for specific high-priority missions is also recommended in Chapter 7.

NSF-Funded Ground-Based Astrophysics Technology Development

The above discussion of the categories and benefits of technology development for the space program apply equally well to ground-based efforts, but the funding patterns are different.

At NSF, relatively near-term technology development is carried out in the course of instrument construction, for example at the national observatories and by the larger community funded by competitive grants from the MRI and ATI programs. The critical advancement of promising new technologies that are not yet ready for implementation, including next-generation and blue-sky technologies, is funded primarily by the ATI program. This aspect of NSF-AST

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[23] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* The National Academies Press, Washington, D.C., 2007.

[24] National Research Council, *An Enabling Foundation for NASA's Space and Earth Science Missions,* 2010.

technology development will be crucial for meeting the needs for the program outlined in this report, including achieving the level of technology development and demonstration required before MREFC funding can be obtained for new major projects.

The types of high-risk, high-payoff technologies that can be transformative frequently take a large fraction of a decade to bring to the point of a convincing demonstration. An example of the kind of technological breakthrough that NSF is capable of enabling is adaptive optics with laser guide star technologies, which today improve the spatial resolution of ground-based images by factors of 20 to 50. The current outstanding performance of adaptive optics on 8- to 10-meter telescopes took more than a decade to achieve.

In view of the higher risk of potentially transformative technology development, one would expect ATI to have a substantial pipeline of projects under way with the realization that many will fail, but a few will succeed in dramatic fashion. In the decade from 1998 to 2008, ATI proposals had a somewhat higher rate of approval for funding than the average for NSF-AST, and the committee thinks that this is appropriate, given the great potential of new technologies for astronomy. The committee received community input in the form of white papers on the funding needs for technology development in areas such as adaptive optics, optical and infrared interferometry, millimeter and submillimeter detector arrays, and high-speed, large-N correlators. The Astro2010 Panel on Optical and Infrared Astronomy from the Ground and Panel on Radio, Millimeter, and Submillimeter Astronomy from the Ground made a convincing case that the current level of ATI funding should be augmented to enable successful pursuit of these highly ranked technology development programs and roadmaps. In Chapter 7 the committee recommends increased funding of the ATI program to meet the technology development needs of the future astronomy and astrophysics program.

DOE-Funded Technology Development

DOE-supported laboratories offer capabilities for technology development that are frequently not accessible at universities. As a result, unique technologies that could be key for astronomical advances are developed at DOE laboratories in support of primary DOE missions, and later adapted for astronomical applications. Examples include (1) the very-large-format detectors that are now being applied to wide-area astronomical imaging in the Dark Energy Camera, and potentially in LSST and WFIRST; (2) the dye lasers developed for the Atomic Vapor Laser Isotope Separation Program that were later modified and adapted for use in laser guide star adaptive optics systems; (3) the electron beam ion traps that were used to measure atomic physics processes for DOE's nuclear weapons mission and subsequently used to measure cross sections relevant to astronomical X-ray spectroscopy; and

(4) the technologies from high-energy physics that are being used very successfully in the Fermi Gamma-ray Space Telescope.

DOE has been supporting specific technology development activities for JDEM and LSST, as well as more general technology development for TeV experiments and cosmic microwave background polarization experiments. Continuation of these activities is of great importance to the committee's recommended program.

LABORATORY ASTROPHYSICS

The Scope and Needs of Laboratory Astrophysics

Laboratory astrophysics plays an important role in ensuring the success of current and future missions and observatories, as highlighted in four of the five Science Frontiers Panel reports. The field of laboratory astrophysics comprises experimental and theoretical studies of the underlying physics that produces observed astrophysical processes. Astronomy is primarily an observational science, detecting light generated by atomic, molecular, and solid state processes, many of which can be studied in the laboratory (see Figure 5.9). Our understanding of the universe also relies on knowledge of the evolution of matter (nuclear and particle physics) and of the dynamical processes shaping it (plasma physics), substantial parts of which can be studied in the laboratory.[25] As telescope capabilities expand in wavelength coverage and precision, laboratory astrophysics plays an increasingly important role in the interpretation of data. At the same time, support for laboratory astrophysics has eroded, and a more robust system of funding to support personnel, equipment, and databases is needed to ensure efficient use and interpretation of hard-won astronomical data.

Traditionally research in astronomy has required atomic and molecular transition data for use in understanding spectra at wavelengths ranging from radio through X-ray wavelengths and for nuclear interaction cross sections. These topics were also at the forefront of research in their respective areas of physics, with the generation of such data heavily supported by NSF-PHY and DOE. There have always been some efforts focused entirely on astrophysics, but the bulk of the data came "for free" from the physics community and especially the national laboratories. The frontiers of physics have evolved, particularly in the field of atomic, molecular, and optical science, and little work of this type is now done

[25] Specifically, laboratory astrophysics studies processes such as atomic and molecular transitions to obtain wavelengths, oscillator strengths, branching ratios, and collision cross sections; nuclear reactions to obtain important cross sections for nucleosynthesis and cosmic-ray spallation; plasma dynamics, transport, and dissipation processes to understand how gases respond to magnetic fields; and chemical reactions in the gas phase and on the surface of dust grains.

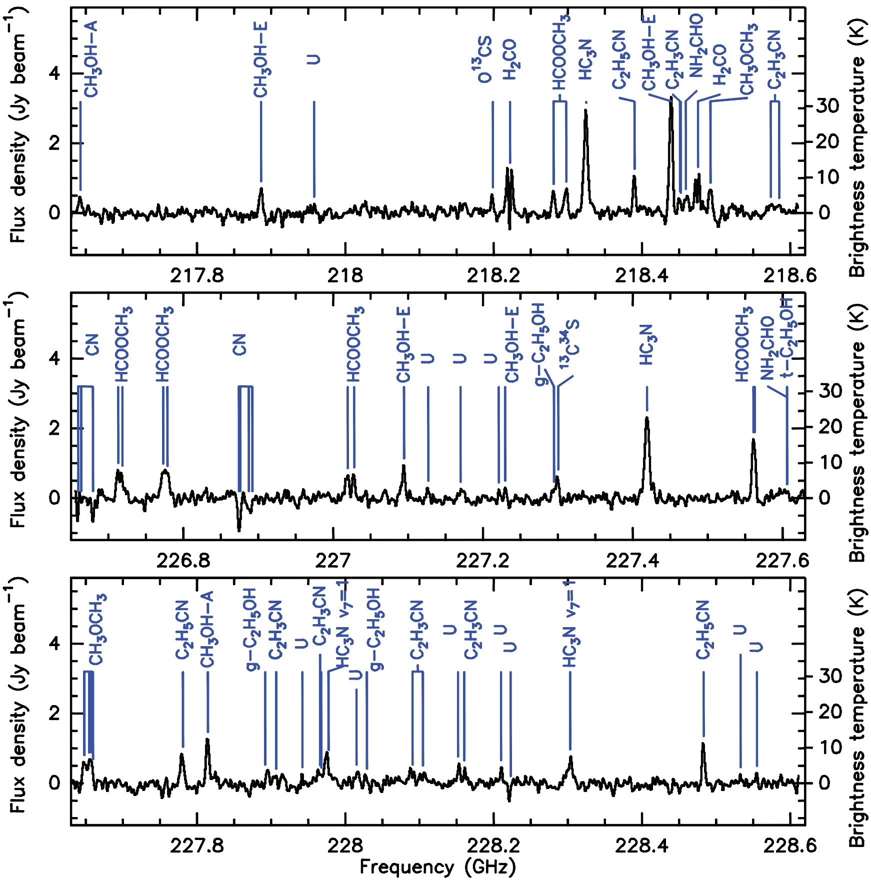

FIGURE 5.9 The richness of the submillimeter spectrum for probing molecular chemistry in regions where stars are born, illustrated with SMA data. Note the number of lines that are at present unidentified ("U"). The promise of SMA, ALMA, and CCAT will be enhanced with additional laboratory astrophysics work. SOURCE: C.L. Brogan, T.R. Hunter, C.J. Cyganowski, R. Indebetouw, H. Beuther, K.M. Menten, and S. Thorwirth, Digging into NGC 6334 I(N): Multiwavelength imaging of a massive protostellar cluster, Astrophysical Journal 707:1-23, 2009. Reproduced by permission of AAS.

in physics departments. At the same time, astronomy's needs have expanded with the progression into new wavelength regimes and the rapid increase in measurement capabilities. For example, precision experiments on magnetized plasmas under astrophysical conditions are becoming available, as are high-energy-density experiments that make use of giant lasers and magnetic pinches to create relevant conditions for heating and shock propagation. In addition, it is possible to use these experiments to advance understanding of magnetic reconnection, which is of vital importance in solar physics. The combination of these factors leads to a need for an increase in the level of support for laboratory astrophysics.

There is also an increased interest in non-traditional areas of laboratory astrophysics such as high-energy-density phenomena. Realization of the importance of magnetized plasmas in interstellar and intergalactic space has generated a need for basic information on the behavior of such plasmas, often in physical regimes far from those currently being studied for their application to magnetic fusion reactors. Laboratory measurements will allow us to understand the formation of molecules in interstellar space and stellar atmospheres, both critical for studies of star formation, for example by studying the complex chemical reactions on the surface of dust grains. DOE's high-energy-density facilities[26] will be able to host laboratory astrophysics experiments relevant to outstanding questions in radiative hydrodynamics, equation-of-state measurements relevant to planetary interiors, and turbulent flow. Those facilities are also performing experiments important to high-energy astrophysics, specifically involving the behavior of hot plasmas and dynamical magnetic field configurations.

The Science Frontiers Panel reports call out specific needs for research in laboratory astrophysics in order to accomplish the proposed research objectives for the next decade. New capabilities require expanded laboratory astrophysics research in the X-ray, UV, millimeter and submillimeter, and IR regimes as missions such as Herschel, JWST, and ALMA go forward. The SFP reports highlight the need for tabulation of spectral features for ions, molecules, and clusters of atoms. Additionally, measurements of gas-phase cross sections, for example of the polycyclic aromatic hydrocarbon molecules found in star-forming regions, are needed to understand the absorption features seen in the spectra of galactic objects. A better understanding of dust and ice absorption spectra and the chemistry of molecule formation is also needed.

The Funding Challenge

NSF-PHY support for laboratory astrophysics has declined to about one-third of that provided two decades ago. Despite an increase in the number of NSF-AST laboratory astrophysics awards in atomic and molecular physics, the combined NSF-PHY plus NSF-AST laboratory astrophysics support has fallen to about half of what it was 20 years ago.

Short-term funding for laboratory astrophysics, such as that tied to observing cycles, is inadequate for the health of stable laboratory astrophysics programs, and

[26] Such as Z and ZR (Sandia National Laboratories), Omega (University of Rochester Laboratory for Laser Energetics), the National Ignition Facility (Lawrence Livermore National Laboratory), and the Princeton Plasma Physics Laboratory.

some source of stable base funding is needed to support experimental facilities. National laboratories, especially those under the Department of Energy's Office of Science and the National Nuclear Security Administration, may be the most dependable long-term reservoir of capability, given that most of these topics are no longer central to the interests of basic physics at universities. The work of compiling the data into useful catalogs and databases is probably still best done by astronomers, and it is vital to maintain databases of important astrophysical results. Such work might be done at national laboratories or at major data centers but has to be coordinated among all investigators.

CONCLUSION: DOE national laboratories, including those funded by the Office of Science and the National Nuclear Security Administration, have many unique facilities that can provide basic astrophysical data.

In summary, the need for laboratory astrophysics has increased because of new and highly capable observing modes that require investigation and because of the relevance of laboratory astrophysics to other physics and engineering problems. Thus a systematic, long-term, and robust funding strategy is required in order to ensure successful scientific returns from missions and programs. Support requires people, instrumentation, and maintenance of databases. NSF-AST support has been increasing, but at far from a sufficient rate to compensate for the loss of input from the atomic physics community and the increased needs of modern astronomical observations.

RECOMMENDATION: NASA and NSF support for laboratory astrophysics under the Astronomy and Physics Research and Analysis program and the Astronomy and Astrophysics Research Grants program, respectively, should continue at current or higher levels over the coming decade because laboratory astrophysics is vital for optimizing the science return from current and planned facilities. Missions and facilities, including DOE projects, that will require significant amounts of new laboratory research results to reach their science goals should include within their program budgets adequate funding for the necessary experimental and theoretical investigations.

6

Preparing for Tomorrow

Whereas Chapter 5 focuses on core elements of the national astronomy enterprise that are supported across federal agencies, this chapter looks at major current and near-term agency-specific activities and also offers recommendations on agency strategy for future facilities development. These agency-specific facilities, missions, and projects often involve partnerships, as discussed in Chapter 3, which may be international, interagency, or public-private in nature. Support of astronomy in the United States extends beyond federal government funding and includes support provided by several state governments for ground-based astronomy and observatories, usually through state universities, as well as private support for both operational and proposed ground-based telescopes.

OPERATING AND UPCOMING PROJECTS, MISSIONS, AND FACILITIES

Department of Energy

The increasing involvement of the Department of Energy (DOE) Office of High Energy Physics (OHEP) in particle astrophysics and cosmology is driven by the deepening scientific connection between OHEP's fundamental physics program and astrophysics. A 2008 report from DOE's High Energy Physics Advisory Panel (HEPAP) described the cosmic frontier as one of three interconnected core areas of particle physics (along with the energy frontier and the intensity

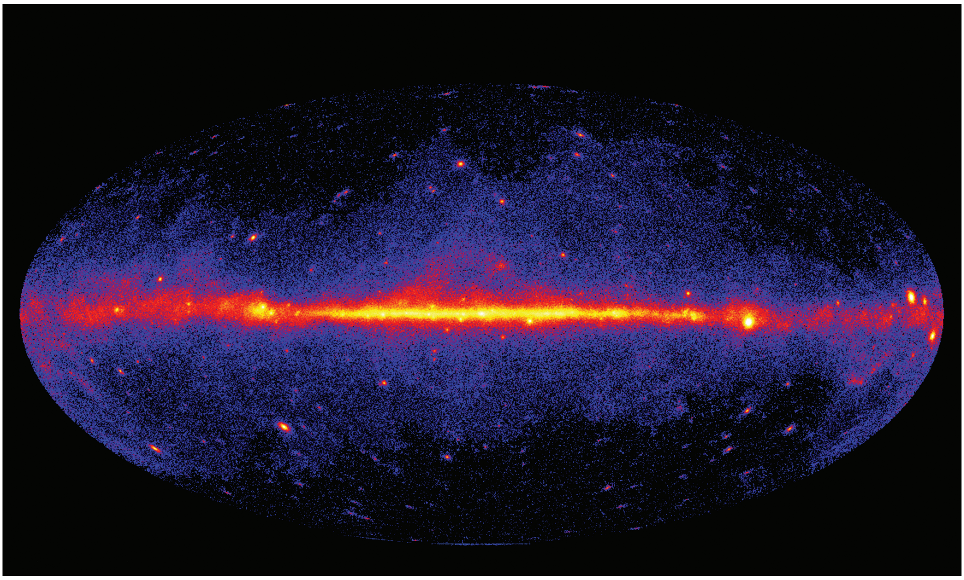

FIGURE 6.1 All-sky map as observed by the Fermi Gamma-ray Space Telescope. The bright band of gamma rays comes from unresolved sources associated with our Milky Way galaxy. Roughly 700 point sources that can be identified with known objects are seen, as are another 600 unidentified sources, including many relativistic jets associated with other galaxies. SOURCE: NASA/DOE/International Fermi Large Area Telescope Collaboration.

frontier).[1] Several national laboratories and the university community are involved in a program with a budget of roughly $80 million in FY2009 (out of a total OHEP budget of about $800 million) and in some scenarios this amount is projected to increase to $160 million by the end of the decade. In 2009, HEPAP's Particle Astrophysics Scientific Assessment Panel (PASAG) was charged with recommending a prioritized program in particle astrophysics for DOE. The PASAG report is discussed further in Chapter 7.[2]

DOE is currently supporting a number of important astrophysics projects—including Auger-South, the Ultra High Energy Cosmic Ray Observatory in Argentina, the Very High Energy Gamma Ray Telescope (VERITAS) in Arizona, the Large Area Telescope (LAT) onboard the Fermi Gamma-ray Space Telescope (Figure 6.1), sev-

[1] U.S. Department of Energy, *U.S. Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years*, Report of the Particle Physics Project Prioritization Panel, Office of High Energy Physics, U.S. Department of Energy, May 29, 2008, available at http://www.er.doe.gov/hep/panels/reports/hepap_reports.shtml.

[2] U.S. Department of Energy, *Report of the HEPAP Particle Astrophysics Scientific Assessment Group (PASAG),* October 23, 2009, available at http://www.er.doe.gov/hep/panels/reports/hepap_reports.shtml.

eral dark energy projects including the Baryon Oscillations Spectroscopic Survey on the Apache Point Observatory 2.5-meter telescope, and a new Dark Energy Camera to be installed on the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory in Chile, small but pioneering efforts on CMB research, and R&D for upcoming projects. Many of these investments are collaborative with either NASA or NSF (NSF-AST and NSF-PHY). In addition, DOE supports a vibrant program of underground dark matter direct-detection experiments and related research and development as part of the cosmic frontier core area. DOE also continues to provide adaptive optics (AO) expertise for instruments on ground-based telescopes. High-energy-density facilities of its National Nuclear Security Administration and laboratory experiments growing out of the Fusion Energy Sciences program play an increasing role in laboratory astrophysics.

National Aeronautics and Space Administration

NASA successfully operates a fleet of nine space telescopes at present and collaborates on several foreign missions (Box 6.1). The annual operating astrophysics budget is roughly $1 billion. All major astrophysics projects are managed by NASA centers,[3] whereas smaller Explorer-class spacecraft experiments can be led by university-based teams. What is striking about the past decade is that nearly all space astrophysics missions have surpassed expectations, both in the technical performance achieved and in the scientific discoveries made. This remarkable accomplishment is one in which the nation can take great pride. Two European space missions with significant U.S. participation, Herschel, a far-infrared telescope, and Planck, a cosmic microwave background experiment, have been launched recently and appear to be working very well. X-ray telescopes led by Japan (Suzaku) and Europe (XMM-Newton) are also producing exciting results and have significant U.S. participation and contributions.

The largest space telescope currently under construction is the James Webb Space Telescope (JWST; Figure 6.2). It was the top large space mission recommended as a result of the 2001 decadal survey[4] and is a successor to both the Hubble Space Telescope and the Spitzer Space Telescope. It is scheduled for launch in 2014. The ambition (the cost exceeds $5 billion) and challenge (the mirror is 2.5 times the diameter of the Hubble mirror) represented by JWST have led to delay in the remaining space astrophysics program proposed in the 2001 decadal survey. JWST

[3] Typically one of the following: Ames Research Center, Goddard Space Flight Center, or Jet Propulsion Laboratory.

[4] National Research Council, *Astronomy and Astrophysics in the New Millennium*, The National Academies Press, Washington, D.C., 2001. Available at http://www.nap.edu/catalog.php?record_id=9839.

BOX 6.1
Space Telescopes Operated by NASA or with U.S. Participation (and operating spectral bands)

Great Observatories

Chandra (X-ray)
Hubble (infrared, optical, ultraviolet)
Spitzer (infrared)

Mid-size Telescopes

Fermi (gamma ray)
Kepler (optical)

Explorers

GALEX (ultraviolet)
RXTE (X-ray)
Swift (X-ray)
WISE (infrared)

Foreign Telescopes with U.S. Participation

Herschel (infrared)
INTEGRAL (gamma ray)
Planck (radio)
Suzaku (X-ray)
XMM-Newton (X-ray)

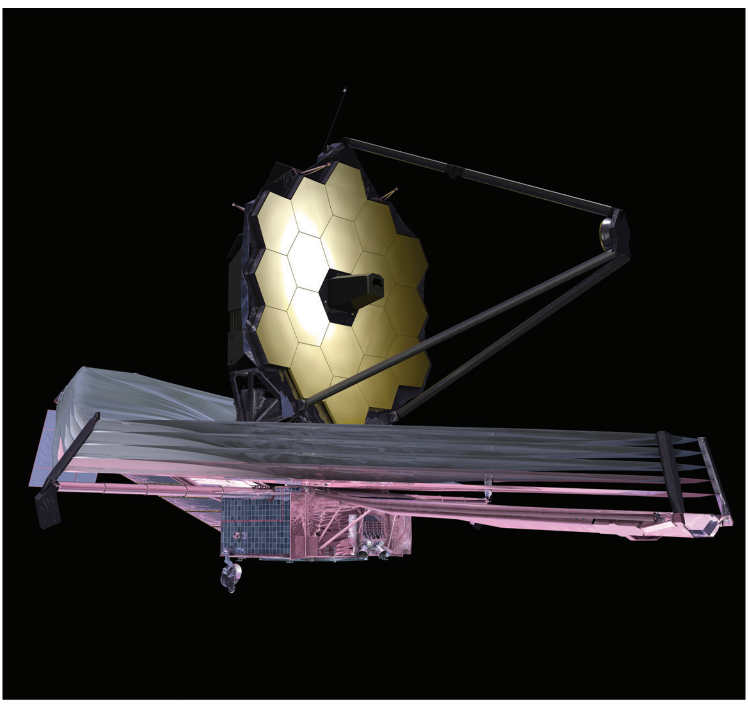

FIGURE 6.2 Artist's drawing of the James Webb Space Telescope. SOURCE: NASA.

will be operated for 5 years, with enough fuel to allow an extension to 10 years. A second infrared telescope, SOFIA, operates out of a Boeing 747 airplane and is due to begin full operations in 2 years. The only other U.S.-led space astrophysics missions currently under construction are the Explorer X-ray missions NuSTAR (to be launched in 2012) and GEMS (scheduled for 2014). There is significant U.S. participation via the Explorer program in the Japanese-led X-ray telescope Astro-H, scheduled for launch in 2014.

NASA also has a balloon program and a suborbital rocket program. Both are highly effective in terms of the scientific results they produce and the fast turn-around they allow, with typically less than 3 years between concept development and flight.[5]

NASA also operates the Infrared Telescope Facility (IRTF) in Hawaii and participates as a one-sixth partner in the W.M. Keck Observatory, also in Hawaii. These NASA programs recognize the importance of optical-infrared data from ground-based telescopes in planning and preparing for, and in interpreting the results from, its space missions—in astrophysics at gamma-ray through mid-infrared wavelengths and in planetary science from numerous in situ locations around the solar system.

NASA holds regular senior reviews to decide which missions to terminate, and it is anticipated that every one of its currently orbiting space telescopes, including Hubble (which needs an expensive de-orbiting mission), will cease operations before the end of the decade. SOFIA, which has operations costs of $70 million per year, will be subject to a senior review after 5 years of operations. Thus, with the possible exception of JWST and SOFIA, none of the missions operating or started today are expected to be operational at the end of the decade.

Summarizing the cost and the frequency of appearance of new capabilities, Figure 6.3 shows NASA missions operating during the past two decades and expected during 2010-2020. The chart illustrates the shift from a mix of mission sizes in the 1990s, to no flagships but a number of smaller missions launched in 2000-2010, to one or possibly two flagships and many fewer smaller missions projected for 2010-2020. Part of this evolution is a result of growing mission complexity. However, the percentage of the NASA Astrophysics Division budget being spent on large missions has been relatively constant for most of the past two decades. The overall lack of mission opportunities is due to the combination of a decrease in the available budget and the increase in expenditures on missions currently operating. The number of missions in operation is large compared to the past several decades.

[5] National Research Council, *Revitalizing NASA's Suborbital Program: Advancing Science, Driving Innovation, and Developing a Workforce,* The National Academies Press, Washington, D.C., 2010.

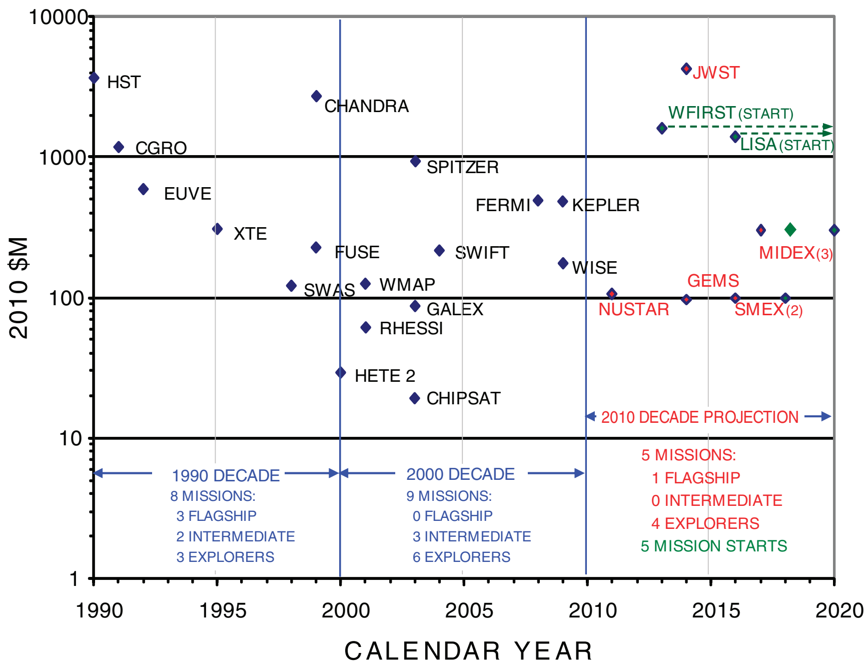

FIGURE 6.3 NASA Science Mission Directorate/Astrophysics Science Division mission cost over time, including future projections, 1990 to 2020. Red diamonds correspond to the year of launch; green diamonds indicate a project start (though not necessarily launched within the decade). Flagship missions are those that are not cost constrained at selection, whereas intermediate and Explorer-class missions are so designated by their cost.

National Science Foundation

The NSF Division of Astronomical Sciences (NSF-AST) supports versatile facility suites in gamma-ray astronomy, optical and infrared astronomy, millimeter and submillimeter astronomy, radio astronomy, and solar astronomy (Box 6.2). The ground-based optical and infrared (OIR) telescopes operate from 0.3 to 20 micrometers and include facilities for both night-time astronomy and for day-time solar studies. The ground-based radio telescopes operate at submillimeter to centimeter wavelengths. For all of these facilities the observing time is competed, typically through bi-annual or tri-annual proposal processes. About $250 million of the roughly $300 million total astronomy and astrophysics expenditures flows through NSF-AST. The remainder is associated with NSF's Division of Physics (NSF-PHY; including particle and nuclear astrophysics), Division of Atmospheric and Geospace Sciences (NSF-AGS), and Office of Polar Programs (NSF-OPP).

BOX 6.2
Major U.S. Public Ground-Based Telescopes

Radio
- Arecibo
- CARMA
- CSO
- EVLA
- GBT
- VLBA

Solar
- Dunn
- GONG
- McMath-Pierce

Gamma Ray
- VERITAS

Optical and Infrared
- Blanco (optical)
- Mayall (optical)
- SOAR (optical)
- WIYN (optical)
- IRTF (infrared) (also NASA)
- Gemini N (optical and infrared)
- Gemini S (optical and infrared)
- Keck (optical and infrared) (also NASA)

Substantial facility investments include LIGO and IceCube, which may yield astronomical discoveries this decade.

The NSF-AST-supported radio observatories have been judged as world-leading, on the basis of both their technical performance and the desire of radio astronomers worldwide to use them. Radio telescopes operated by the National Radio Astronomy Observatory (NRAO) include the Expanded Very Large Array (EVLA), the Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA); the National Astronomy and Ionosphere Center (NAIC) operates Arecibo observatories. These centimeter-wavelength facilities provide the highest-resolution and largest-collecting-area instruments in the world. Following the recommendations of the 2006 NSF-AST senior review,[6] funding for Arecibo ($8 million per year) and for NRAO's VLBA, both still unique facilities, is being ramped down to optimize the program and to release funds for operating new facilities. The soon-to-be-commissioned (in 2013) $1 billion Atacama Large Millimeter/submillimeter Array (ALMA) is an international collaboration involving partners in North America, Europe, and East Asia, with Chile as the host country (Figure 6.4). In addition to these nationally managed facilities, NSF-AST funds operations and development at the university-based CARMA, ATA, and CSO ($8 million per year combined through the URO program), and NSF-OPP funds SPT ($2.5 million per year), which together at

[6] National Science Foundation, *From the Ground Up: Balancing the NSF Astronomy Program,* Report of the NSF Division of Astronomical Sciences Senior Review Committee, National Science Foundation, Arlington, Va., 2006.

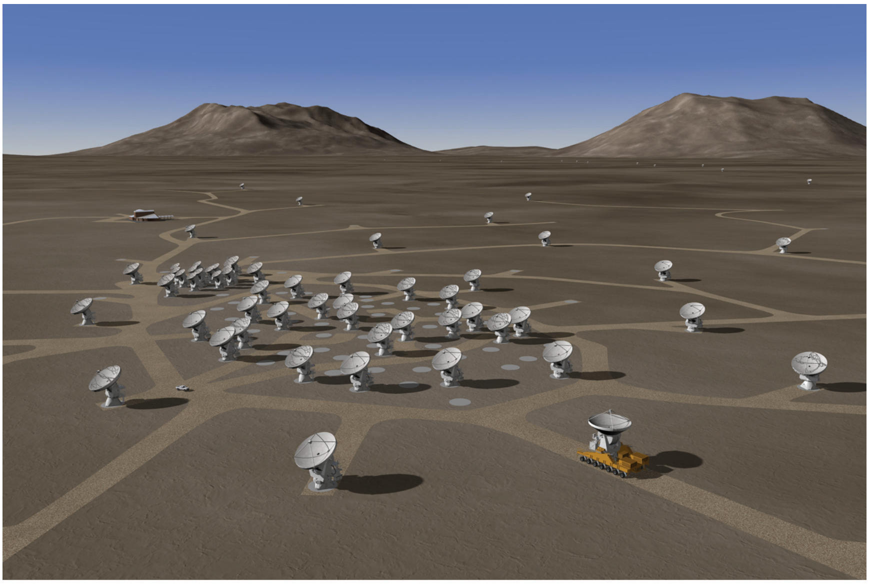

FIGURE 6.4 Artist's conception of the ALMA array with roads, in the extended configuration. SOURCE: ALMA (ESO/NAOJ/NRAO).

$10 million can be compared to NRAO funding ($67 million per year). The small facilities provide unique scientific capabilities, training, and technical development, particularly for millimeter and submillimeter observations.

The NSF-AST-supported ground-based OIR facilities include the National Optical Astronomy Observatory (NOAO)-operated optical telescopes at Kitt Peak in Arizona and Cerro Tololo in Chile that are 4 meters (Mayall and Blanco) or smaller in diameter and are aging in terms of infrastructure. They also include a half share with international partners—the United Kingdom, Canada, Chile, Australia, Brazil, and Argentina—in each of the 8-meter northern (Mauna Kea) and southern (Cerro Pachon) Gemini telescopes (Figure 6.5). The Blanco and Mayall telescopes are being refurbished, partly in connection with DOE-supported dark energy projects. Gemini-North features an operational laser guide star AO system, and there is the promise within a few years of multi-conjugate AO at Gemini-South to produce high-resolution images over a wide field of view. However, as discussed in the NSF-AST senior review and elsewhere, the Gemini Observatory has been slow in providing the community with the world-class instruments that it needs to carry out its research program and has incurred operations costs that are larger than were anticipated. The challenges arose partly because of a then-multinational management structure and partially because of the early choice of a queue-based observing mode.

FIGURE 6.5 Gemini-North with southern star trails. SOURCE: Gemini Observatory/AURA.

NSF-AST also supports instrumentation on private observatories through its Telescope System Instrumentation Program (TSIP) ($4 million per year) program and ReSTAR ($3 million per year)-based expenditures. Small in comparison to the investments in NOAO plus Gemini ($43 million per year), these development funds provide access for the community to both unique and workhorse scientific capabilities that complement those available on the NSF-run facilities.

The Advanced Technologies and Instrumentation (ATI) and Major Research Instrumentation (MRI) programs provide technology development and instrumentation support for radio, optical and infrared, and solar facilities.

In solar astronomy, the Advanced Technology Solar Telescope (ATST) on Haleakala in Maui, Hawaii, received an American Recovery and Reinvestment Act commitment for about half of ATST's roughly $300 million construction cost, and the project has formally started. Managed within NSF-AST, ATST's other construction costs will come from NSF's Major Research Equipment and Facilities Construction (MREFC) program. A world-leading facility, with an off-axis 4-meter mirror and an optical design optimized to eliminate scattered sunlight, ATST will operate with the most advanced solar AO system in the world, making possible, for example, a direct comparison of the magnetic structures that accompany solar granulation with the predictions of the latest computational models (Figure 6.6).

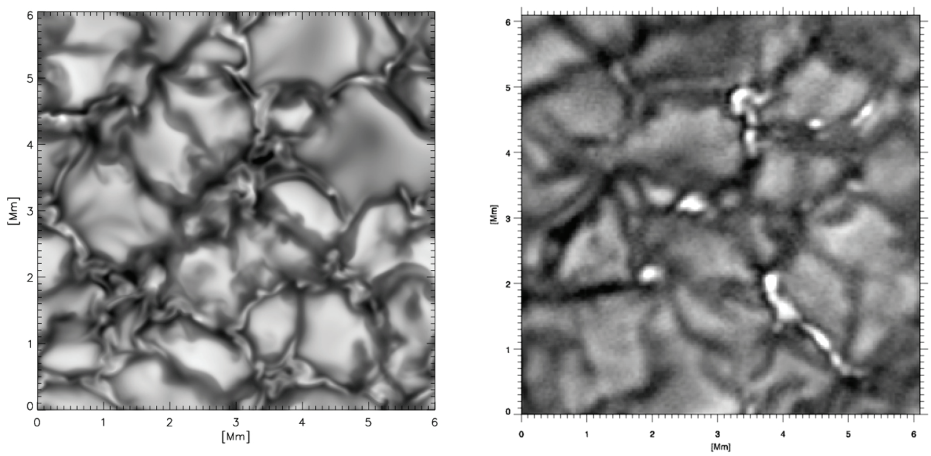

FIGURE 6.6 Magnified view of solar convective and magnetic structures. *Left:* Computer simulation of convection on the solar surface, together with emergent magnetic fields (twisted structure surrounding each granule). *Right:* Adaptive optics image of solar convection using the National Solar Observatory's Dunn Solar telescope. White threads map out the emergent magnetic field surrounding each granule. ATST will have sufficient spatial resolution to quantitatively test these simulations against a statistically significant sample of solar data. SOURCE: *Left*—A. Vögler, S. Shelyag, M. Schüssler, F. Cattaneo, T. Emonet, and T. Linde, Simulations of magneto-convection in the solar photosphere, Astronomy and Astrophysics 429:335-351, 2005, © ESO, reproduced with permission. *Right*—Thomas Rimmele, National Solar Observatory.

It will allow study of intense solar magnetism on the fine and complex scales that are likely to be present in nearly all stars, but which can finally be resolved with the 0.05-arcsecond spatial resolution that ATST will provide. NSF-AST also operates the National Solar Observatory (NSO) and its suite of smaller solar telescopes located at multiple sites.

Summarizing the activity scale and the frequency between the appearance of new flagship capabilities among NSF-AST facilities, during the 1990s the optical Gemini facilities were built, during the 2000s the Expanded Very Large Array and the ALMA radio facilities were constructed with ALMA slated for completion early next decade, and the 2010s will witness construction and operation of the solar facility ATST. Although construction money has come recently from the NSF MREFC line, operations for and development of these new flagships fall to NSF-AST—as do these costs for the existing optical, radio, and solar facilities mentioned above. The increasing scale and complexity of astronomical machinery brings increasing operations and development needs.

Within NSF-AST, resource allocations are approximately 56 percent for current facility operations, 10 percent for instrumentation, and 7 percent for future facilities and advanced technology development. According to information provided by the Astro2010 Infrastructure Study Groups, 23 percent is spent on individual investigator grants in support of research. Approximately 61 percent of the funding for facilities goes to national and university-based radio, 33 percent to national and university-based optical, and 6 percent to solar telescopes. In the committee's view this allocation of resources is unbalanced: existing facilities are not being exploited efficiently because not enough is invested in modern instrumentation and in supporting the investigators who produce the science from these facilities and, furthermore, not enough is invested in the future through advanced technology development. Unless the budget increases, the only way to render balance is to close operating facilities, and the mechanism for doing this is senior reviews.

CONCLUSION: Maintaining an appropriate balance in NSF's astronomy and astrophysics research portfolio and, by extension, balance in the health and scientific effectiveness of the NSF facilities requires a vigorous periodic senior review.

Senior reviews are major endeavors and should be undertaken very seriously. They should be seen as a means for ensuring good stewardship of the NSF program.

RECOMMENDATION: NSF-Astronomy should complete its next senior review before the mid-decade independent review that is recommended elsewhere in this report, so as to determine which, if any, facilities NSF-AST should cease to support in order to release funds for (1) the construction and ongoing operation of new telescopes and instruments and (2) the science analysis needed to capitalize on the results from existing and future facilities.

TOWARD FUTURE PROJECTS, MISSIONS, AND FACILITIES

Department of Energy

As discussed above and in earlier chapters, the connection between astronomy and physics has strengthened considerably over the past decade. There is strong mutual interest in the two communities in dark energy, dark matter physics of the very early universe, gravitation, CMB, gamma-ray astrophysics, and cosmic-ray physics. University physicists and national laboratories have already collaborated productively with scientists from more traditional astronomical backgrounds on highly successful ventures. The strength of these collaborations at the working level has derived from the complementary perspectives on the science and the different technical skills and experience contributed by these two communities—

complementarity that has turned out to be crucial. For example, astronomers collectively understand about building telescopes, crafting practical observing programs, and launching spacecraft, while physicists have contributed unique capabilities in detectors, electronics, and data handling.

Future progress will be enabled by DOE's current support for development of the Joint Dark Energy Mission (JDEM) in space, the Large Synoptic Survey Telescope (LSST) camera, and CMB science efforts. The committee recommends in Chapter 7 continuing steps consistent with the DOE mission that take advantage of present day physics-astrophysics science synergies.

National Aeronautics and Space Administration

Based on the recommendations of the 2001 decadal survey, AANM,[7] beyond that for James Webb Space Telescope, NASA is currently supporting development of a Space Interferometry Mission (SIM) and technology for a future Terrestrial Planet Finder. Following publication of a 2003 NRC report[8] there has also been significant activity toward JDEM in possible partnership with DOE and/or ESA.

The sustained success of NASA's astrophysics program rests on its effective leveraging of activities ranging from large flagship missions to smaller more focused Explorer missions, down to the suborbital, data analysis, theory, technology development, and laboratory astrophysics programs. This diversified portfolio maximizes scientific exploitation of the missions, paves the way toward future missions, and maintains and develops the expertise that will enable the United States to keep its world leadership in space astronomy. Prudent investment in the core supporting activities also has proven to minimize risk and reduce the end-to-end costs of major missions, by addressing critical design issues before missions enter their construction phases.

In the course of formulating recommendations that include large, medium, and small missions, as well as targeted augmentations to some of the core supporting activities, the committee considered broader issues of balance between a range of elements across the NASA program: between larger and smaller missions; between NASA-led and international-partner-led missions; between university-led and NASA-center-led missions; between mission-enabling and mission-supporting activities (technology development, Suborbital program, theory, ground-based observing) and the missions themselves; between mission construction/operation and data archiving and analysis; and between extended mission support for operating

[7] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

[8] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for a New Century*, The National Academies Press, Washington, D.C., 2003.

missions versus funding of new missions. During its deliberations the committee attended to the general principle of balance in developing its recommended prioritization of projects within the NASA Astrophysics Division program during the coming decade.

In terms of mission size balance, the committee values the impressive science value per dollar achieved with a healthy Explorer program, so much so that an enhancement to the Explorer program is its second-ranked large space project recommendation in Chapter 7. Likewise, the committee recommends strong support for the suborbital and balloon programs. Apart from providing a high science return, these smaller-scale activities provide opportunities for university-led projects, which in turn train future instrumentalists and leaders in space astrophysics and maintain a strong skill base outside the NASA centers. They also provide testbeds for future technologies and vital science inputs for planning future larger missions. These same considerations motivate the committee's recommendations for maintaining or enhancing the support for non-mission specific technology development.

As discussed in Chapter 3, international collaborations are becoming a major factor in current and future missions. Nearly all of the large space-based projects recommended in Chapter 7 have some international element. International collaborations can carry administrative, technical (e.g., ITAR), and even political burdens. Overall, however, the committee views this evolution as a means of maximizing science and minimizing redundancy in an era of tight funding.

A final important balance element is between support for the development and operation of missions and the support for the archiving, analysis, and scientific interpretation of the data realized from the missions, including theoretical and computational modeling. Although these activities add up to a minor fraction of total mission costs, funds are often re-appropriated from these categories when costs overrun in other components of the NASA SMD budget. These vital elements of NASA Astrophysics Division funding must be protected from overruns elsewhere.

National Science Foundation

Based on the recommendations of the 2001 decadal survey, AANM, NSF is currently supporting development of LSST and technology related to a Giant Segmented Mirror Telescope (GSMT), Square Kilometer Array (SKA), and Frequency Agile Solar Radiotelescope (FASR). A desire for healthy balance between future facilities, current facilities, and core activities such as those described in Chapter 5 led the committee to consider evolution in the existing optical and infrared; radio, millimeter, and submillimeter; and solar observatory telescope systems in U.S. ground-based astronomy.

A Future Optical and Infrared System

Whatever new telescopes NSF decides to support in the decade to come, a guiding principle in planning a future optical and infrared (OIR) system of telescopes is maintaining an appropriate balance between major national facilities and a vibrant university-based program, as well as ample provision for the longer-term future. This future is certain to include larger and ever-more capable telescopes.

AANM developed the concept of treating the federally supported and independent OIR observatories in the United States as an integrated system, and advocated this concept as a means to increase community access to large-aperture telescopes through the TSIP. During the past decade there have been several reviews of the OIR system, including the 2006 NSF-AST senior review and the subsequent NOAO-led ALTAIR and ReSTAR committee reports[9] that addressed community needs for large and small telescopes, respectively. Together these studies identify a series of critical needs that must be balanced to optimize the overall OIR system. The most important of these include:

1. Development of future large telescope facilities, specifically LSST and GSMT, including a federal leveraging of private funding so as to ensure open access to a share of time on these facilities and to their data archives. Currently, around 5 percent of the NSF-AST OIR facilities, instrumentation, and development budget is allocated to future activities.
2. Support of the NOAO and Gemini public observatories, providing open community access to telescopes with aperture up to 8 meters, and coordination of current and future OIR facilities and instrumentation initiatives. Currently, this accounts for around 80 percent of NSF-AST OIR funding.
3. Investment in new and upgraded instrumentation for privately operated telescopes, to enhance the scientific potential of these facilities and to provide public access to a share of the observing time—via TSIP, ReSTAR, MRI and ATI, and a mid-scale instrumentation program—currently around 15 percent of funds.

These reports also concluded, and this committee concurs, that following the current unbalanced funding path and investing relatively little in future large projects will further diminish the U.S. presence in international OIR astronomy. The challenge is to achieve a better balance that will enable significant federal participation in LSST and GSMT, while retaining sufficient access to smaller telescopes in private or public hands, to carry out a balanced science program with benefit for both the public and private sectors. After considering various options,

[9] ReSTAR report, available at http://www.noao.edu/system/restar/files/ReSTAR_final_14jan08.pdf. Accessed May 2010. ALTAIR report, available at http://www.noao.edu/system/altair/. Accessed August 2010.

the committee found that the scientific output of the OIR system would be optimized by re-allocating support to provide more for instrumentation on the newer telescopes that enable production of the majority of high-impact science papers.[10] If administered through the TSIP and ReSTAR funding rules, in the case of private facilities, such investments would provide increased public access to these existing telescopes.

CONCLUSION: Optimizing the long-term science return from the whole of the U.S. optical and infrared system requires a readjusting of the balance of the NSF-Astronomy program of support in three areas: (1) publicly operated national observatories—the combined National Optical Astronomy Observatory and Gemini facilities that currently dominate spending; (2) private-public partnerships—such as support for instrumentation at and upgrades of privately operated observatories; and (3) investment in future facilities.

Among the newer OIR facilities are the two Gemini telescopes, which can be appropriately instrumented to provide the spectroscopic and near-infrared imaging capabilities that are critical to reap the scientific harvest from ALMA, JWST, and the future LSST. They can also provide some of the 8- to 10-meter-class telescope capability that is needed to fulfill the major scientific initiatives of Astro2010 in exoplanets, dark energy, and early galaxy studies. The Gemini telescopes are now equipped with multiobject spectrographs, integral field spectroscopy capability, and both near- and mid-infrared detectors, with a multi-conjugate adaptive optics capability imminent on Gemini-South; they are now poised to deliver the scientific impact they promise. However, despite its high science potential, the Gemini program does not, in practice, satisfy the requirements of the U.S. astronomical community. The ALTAIR report noted general community dissatisfaction with the current instrument suite, the queue observing mode, and the governance of the observatory. The Panel on Optical and Infrared Astronomy from the Ground found that the Gemini complex management structure created to facilitate international operation prevents the U.S. National Gemini Office from serving as an effective advocate for U.S. interests at a level commensurate with its partnership share. Furthermore, as noted by the 2006 NSF-AST senior review, as well as internal Gemini Observatory reviews, Gemini operations costs are higher than those at other comparable U.S. facilities. The committee concluded that the Gemini

[10] D. Crabtree, Scientific productivity and impact of large telescopes, in *Observatory Operations: Strategies, Processes, and Systems II* (R.J. Brissenden and D.R. Silva, eds.), Proceedings of SPIE, Vol. 7016, doi:10.1117/12.787176, SPIE, Bellingham, Wash., 2008; J.P. Madrid and F.D. Macchetto, "High-Impact Astronomical Observatories," ArXiv eprint arXiv:0901.4552, 2009; accepted for publication in the *Bulletin of the AAS.*

program as currently configured is not serving the needs of the U.S. astronomical community well. The level of future investment in Gemini will presumably be assessable following the next senior review.

The Gemini international partnership agreement is currently under renegotiation, and the United Kingdom, which holds a 25 percent stake, has announced its intent to withdraw from the consortium in 2012. This change presents an opportunity for the remaining partners to restructure the governance, simplify the management, and improve the responsiveness of Gemini. The goals are streamlined operations and decreased operating costs.[11] The savings should be applied to offset the loss of the UK contribution while increasing the U.S. share of observing time. In addition, the Gemini partnership might consider the advantages of stronger scientific coordination with major U.S. science programs. This approach would also provide a good rationale for increasing the U.S. share of Gemini while increasing the scientific output. The committee recognized that unless a new partner is found, some increased cost for Gemini is likely, but it believes that any additional cost should not be in proportion to the added U.S. share of observing time.

NOAO has a valuable role within the OIR system. It provides merit-based access to the small telescopes under NOAO management, it administers TSIP and ReSTAR-based funds for access to a broader range of apertures and instruments, and it serves as a community advocate and facilitator for LSST and GSMT. NOAO could be called on to play a greater role in leading the OIR system, so long as it involves all relevant parties. Actions taken in response to the 2001 decadal survey and the 2006 NSF-AST senior review have led to greater attention to stakeholders in the ground-based community.

However, despite having much better relations with the user community, NOAO's future is not without controversy. As OIR astronomy moves into the 20- to 40-meter-class telescope era, the relevance of the current NOAO facilities will diminish further, along with the level of support that can be justified. Any specific direction on how to find economies within the NOAO budget falls outside the charge of this report and will, presumably, be part of the next NSF-AST senior review. However, the committee notes some options, including consolidation of part or all of the staff and management of NOAO and Gemini; closure or privatization of some of the telescopes; closure or privatization of one of the sites; and a gradual transition in the staffing and staff responsibilities toward an operations-focused model. At the same time, NOAO could also assume a larger role in managing the federal interest in Gemini, LSST, and GSMT. Now is the time for

[11] Gemini is now going through an exercise to cut its operating budget to 75 percent of the present figure, so that the existing partners can increase their shares with no increase in expenses. This effort is partly in response to the community's strong opinion that the Gemini operation is the least cost-effective compared with all the other 8-meter telescopes in the world.

NSF to re-evaluate the OIR system and NOAO's role in it under cost-constrained conditions. Advice from an independent commission including both astronomers and specialists in systems management is one way to address this issue.

RECOMMENDATION: To exploit the opportunity for improved partnership between federal, private, and international components of the optical and infrared system, NSF should explore the feasibility of restructuring the management and operations of Gemini and acquiring an increased share of the observing time. It should consider consolidating the National Optical Astronomy Observatory and Gemini under a single operational structure, both to maximize cost-effectiveness and to be more responsive to the needs of the U.S. astronomical community.

A Future Radio, Millimeter, and Submillimeter System

The ground radio, millimeter, and submillimeter (RMS) telescope system has three crucial elements:

1. World-class facilities using an efficient suite of telescopes based on mature technologies,
2. Unique and important observing capabilities and the development of new technologies and techniques through university-operated observatories, and
3. Specialized principal-investigator-led experiments and surveys that tackle key science challenges and develop new technologies.

The RMS system is funded primarily by NSF. In considering its future, it must find a balance between several competing elements in order to optimize the science delivery at a time of seriously constrained funding. A guiding principle is maintenance of an appropriate balance between major national facilities and a vibrant university-based program. A second principle is provision for the long-term future through a staged program leading toward major participation in all three components of the international Square Kilometer Array, which has enormous scientific potential and enthusiastic support around the globe.

At present, approximately two-thirds ($67 million) of the NSF-AST RMS budget is devoted to NRAO to operate and develop the (E)VLA, Green Bank, and ALMA facilities. The remaining one-third ($33 million) is devoted to future facilities development, technology development, and university-operated observatories and experiments.

While the strength of the RMS system rests on maintaining the balance of the national observatories, university-operated observatories, principal-investigator-led experiments, and technology development, a fundamental problem is the funding pressure that new facilities place on the existing program. The report of the Astro2010 Panel on Radio, Millimeter, and Submillimeter Astronomy from the Ground cites the many new demands on this budget that are likely to arise over the coming decade, including full operations support for ALMA, upgrades to ALMA and other NRAO facilities, technology development for SKA, and increased support of the University Radio Observatory (URO) program. The introduction of new capabilities will require withdrawal of NSF support for some existing facilities. Reprioritization has happened historically under the URO program,[12] and Arecibo and the VLBA, although both still productive and unique in sensitivity and in spatial resolution, respectively, had their funding reduced following the 2006 NSF-AST senior review. Additional savings will surely be needed, and the proper venue for making facility-by-facility funding choices is the senior review process.

CONCLUSION: The future opportunities, worldwide, in radio, millimeter, and submillimeter astronomy are considerable, but U.S. participation in projects such as the Square Kilometer Array is possible only with either a significant increase in NSF-AST funding or continuing closure of additional unique and highly productive facilities.

The committee's recommendations in Chapter 7 address the balance within RMS astronomy through endorsements of medium-scale facilities and funds for technology development.

A Future Solar Observatory System

The NSF-supported National Solar Observatory (NSO; within NSF-AST) and High Altitude Observatory (HAO; within NSF-AGS) are joined by a number of public/private solar observatories, namely Big Bear Solar Observatory (operated by the New Jersey Institute of Technology), Meese Solar Observatory (University of Hawaii), Mt. Wilson Observatory (Carnegie Institution of Washington/Mount Wilson Institute), San Fernando Observatory (California State University, Northridge), and Wilcox Solar Observatory (Stanford University). The funding streams for the independent solar observatories are fragile and have been influenced by significant reductions in the funding for them by the Office of Naval Research and the Air Force Office of Scientific Research. These facilities have good collaborative arrangements with NSO and HAO in the development of instrumentation, in scheduling observing campaigns, and in exchange of personnel, and they

[12] For example, the 42-meter telescope at Green Bank, the 14-meter telescope at the Five College Radio Astronomy Observatory, and the 37-meter telescope at the Haystack Observatory have been shut down already; the Caltech Submillimeter Observatory is slated for closure in 2016.

are particularly valuable in the training of young scientists, thereby functioning as an informal solar observatory system.

The national ground-based solar facilities will be transformed once the Advanced Technology Solar Telescope is completed and becomes operational in 2017. ATST is being built within NSO but has very active participation by HAO and many other university partners. It is likely that the headquarters of NSO will be relocated to enable closer university participation with its scientists and in the training of young researchers. Other solar telescopes operated by NSO in Arizona (McMath-Pierce on Kitt Peak) and in New Mexico (Dunn on Sacramento Peak) are planned for closure to free up resources. ATST operations will require, beyond that amount, an additional $3 million per year for NSO.

Solar observations at radio and millimeter wavelengths continue to be complementary to the optical-infrared programs and the extensive probing at optical and UV wavelengths from spacecraft like the highly successful SOHO, TRACE, STEREO and the recently launched Solar Dynamics Observatory (SDO). Long-wavelength observations elucidate plasma properties in regions of magnetic field reconnection both on the solar disk and off the limb, in the extended corona and its wind streams, and by imaging coronal mass ejections. These observations are being carried out with NRAO facilities such as the VLA and the Green Bank Solar Radio Burst Spectrometer, along with the Owens Valley Solar Array operated by the New Jersey Institute of Technology. Once operational, ALMA will be capable of probing the lower solar atmosphere, including emissions from the most energetic electrons and protons produced in solar flares. With three arrays of steerable antennas and the ability to rapidly sample a broad range of frequencies, the proposed FASR would yield the most direct means of measuring and imaging coronal magnetic fields, the physics of solar flares, and drivers of space weather. FASR would be built by a consortium. The wide field of view afforded by FASR of evolving plasma structures and of associated magnetic fields would be an important complement to the high resolution but localized observations enabled with ATST. FASR was ranked highly by the 2001 survey AANM[13] and also by the NRC's 2003 solar and space physics survey.[14]

As described above, the bulk of the grant funding for solar scientists within NSF comes from AGS, while the facilities funding is split between AGS and AST. This unusual dual division support arrangement for ground-based solar work

[13] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

[14] National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics,* The National Academies Press, Washington, D.C., 2003.

has been noted[15] and differs from the organization of space-based solar physics.[16] Solar physics will change rapidly over the next 5 years as ATST is constructed and deployed and as older facilities are closed. In addition, the field is likely to expand in areas that directly involve solar effects on Earth. A future solar observatory telescope system would benefit from NSF's adoption of a unified approach incorporating how at least two of its divisions develop and support a coordinated ground-based solar physics program.

RECOMMENDATION: NSF should work with the solar, heliospheric, stellar, planetary, and geospace communities to determine the best path to an effective and balanced ground-based solar astronomy program that maintains multidisciplinary ties. Such coordination will be essential in developing funding models for the long-term operation of major solar facilities such as the Advanced Technology Solar Telescope and the Frequency-Agile Solar Radiotelescope, and in the development of next-generation instrumentation for them along with the funding of associated theory, modeling, and simulation science.

[15] National Research Council, *The Field of Solar Physics: Review and Recommendations for Ground-Based Solar Research,* National Academy Press, Washington, D.C., 1989.

[16] NASA has chosen to assign all matters solar to its Heliophysics Science Division within SMD, and the solar and space physics community began its own decadal survey starting in the summer of 2010.

7

Realizing the Opportunities

The preceding chapters of this report present a compelling science program (Chapter 2) and outline the relationship of the federal program to the larger astronomy and astrophysics enterprise (Chapters 3 and 4). They also discuss workforce development and other core activities, the changes in the base program that are prerequisites for substantial new initiatives, and the need to keep existing facilities in balance with the development of new ones (Chapters 5 and 6). This chapter describes the committee's recommended program. After outlining the process followed in carrying out the Astro2010 survey, this chapter discusses how addressing the three major objectives of the recommended science program requires a particular suite of activities. Next, it argues that this same suite addresses the larger science program outlined in Chapter 2. The recommended activities are then described in more detail as elements of the integrated program for the decade recommended to the three agencies that commissioned this report.

PROCESS

Prioritization Criteria

The approach taken by this survey has been to develop a logical program for the decade 2012-2021 that is firmly aimed at realizing identified science priorities and opportunities, especially the key science objectives established below. The recommended program is rooted in the existing research enterprise and is based in part on the availability of new technology that will inspire and enable astronomy and astrophysics in the decade to come. Furthermore, in the development of its recommendations the committee considered the challenges and constraints of the current federal budget environment along with its own independent and critical evaluation of proposed activities. The need for balance across the program was carefully considered.

The committee adopted four major criteria as the basis for prioritization of activities:

- Maximizing the scientific contribution and return identified by the survey process (see Chapter 2);
- Building on the current astronomy and astrophysics enterprise (see Chapters 3, 4, 5, and 6);
- Balancing activities that can be completed in the 2012-2021 decade against making investments for the next decade; and
- Optimizing the science return under highly constrained budget guidelines by assessing activity readiness, technical risk, schedule risk, cost risk, and opportunities for collaboration.

Program Prioritization

The science case developed by the committee in Chapter 2 served as a principal component of the evaluation of proposed activities that was undertaken by this survey. It was drawn from the questions and discovery areas identified by the five Science Frontiers Panels (SFPs) appointed by the National Research Council (NRC) to assist the committee, namely:

- Cosmology and Fundamental Physics,
- The Galactic Neighborhood,
- Galaxies Across Cosmic Time,
- Planetary Systems and Star Formation, and
- Stars and Stellar Evolution.

The charge to and principal findings of the SFPs are summarized in Appendix A. The individual SFP reports describe in more detail the science priorities.[1] The work of these panels formed the foundation for the prioritization process.

[1] See National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2011.

The prioritization process included projects not yet started from the preceding decadal survey, *Astronomy and Astrophysics in the New Millennium* (AANM).[2] The rationale for their review stems from a need to ensure that these research activities are still up to date technologically, that the science questions they tackle remain compelling and a high priority, and that their cost and schedule are still commensurate with the science return. Given the multidecade timescales required for development of major facilities from concept to construction to operation, it should not be surprising that many of these projects have evolved in technical and/or scientific scope since AANM, further motivating their reconsideration.

Because of the need for significant technical expertise in developing a prioritized program from a wide array of candidate ongoing and proposed activities, four Program Prioritization Panels (PPPs) were also established by the NRC to assist the committee in studying technical and programmatic issues within the following areas:

- Electromagnetic Observations from Space (EOS)—activities funded largely by NASA, some with a DOE component;
- Optical and Infrared Astronomy from the Ground (OIR)—activities funded largely by NSF and private entities, some with a DOE component;
- Particle Astrophysics and Gravitation (PAG)—activities funded by NASA, NSF, and DOE; and
- Radio, Millimeter, and Submillimeter Astronomy from the Ground (RMS)—activities funded largely by NSF with some private components.

The charge to the PPPs and their principal recommendations for new activities are summarized in Appendix B. The PPPs started with the SFPs' conclusions on the highest-priority science and then developed a program to address this science optimally. The panels also referred to pertinent NRC reports, as well as reports from the astronomy community. The individual PPP reports contain these and other nonfacility recommendations spanning a range of scales.[3] Each panel was charged to consider only the potential program within its designated subdiscipline. By design this approach results in a combined program that is too large to be implemented in any reasonable budget scenario. It thus fell to the survey committee to synthesize the panel recommendations with additional consideration for the issues discussed in Chapters 3, 4, 5, and 6, and thereby develop a merged implementable program for the entire astronomy and astrophysics enterprise.

[2] National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

[3] National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics,* The National Academies Press, Washington, D.C., 2011.

Cost, Risk, and Technical Readiness Evaluation

As an early step in the survey process (Figure 7.1), the committee issued a request for information to the astronomy and astrophysics community to solicit input on possible future research activities. More than 100 responses proposed significant construction or programmatic activities. Following an initial analysis by the PPPs, the survey committee requested further and more detailed information from a set of activity teams, which was subjected to a novel cost appraisal and technical evaluation (CATE) process (see Appendix C for a detailed discussion of this process). The objective of the CATE process was to judge the readiness, technical risk, and schedule risk for the proposed projects, and then to construct associated cost and schedule estimates. The CATE process was conducted by a private contractor (the Aerospace Corporation) that was hired by the NRC to assist the committee in executing this element of its charge.

Throughout the course of the survey, the committee and the PPPs remained engaged with the contractor to ensure that the contractor understood the key aspects of the proposed activities and the key points of analysis required by the panels and the committee. All elements of a project required to produce an initial science result were included in the assessment. The assessment was intended to include technical development and construction costs, as well as operating costs for a nominal 5-year mission or project execution, but not research costs needed to exploit the

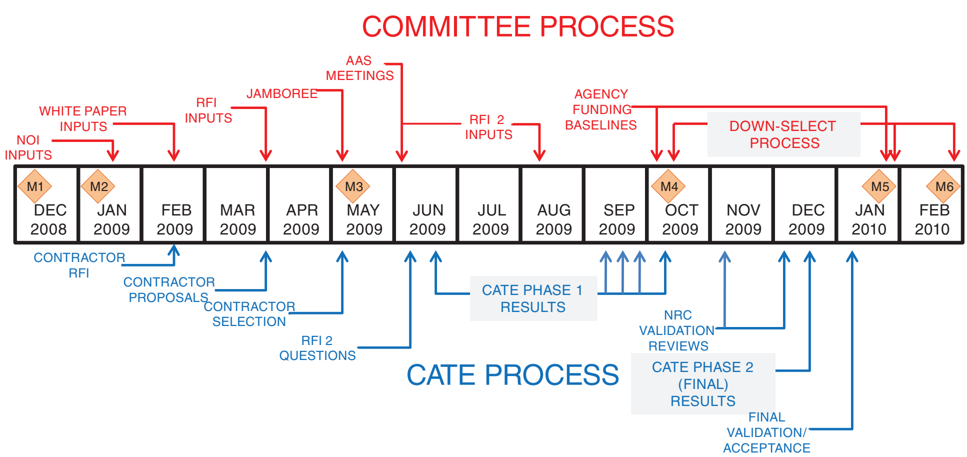

FIGURE 7.1 Time line showing the sequence of the Astro2010 survey's activities and its cost appraisal and technical evaluation (CATE) process. The six committee meetings—including the "Jamboree" meeting involving all four Program Prioritization Panels, the Infrastructure Study Group chairs, the Science Frontiers Panel chairs, and the survey committee—held at key process milestones are indicated by the orange diamonds.

science optimally. For some activities a clear path emerged to deployment from this analysis, while for others it became equally clear that certain milestones would have to be met before the activity could proceed to full implementation. For still other activities, the scientific and technical landscapes were found to be shifting too rapidly for the survey to make a definitive recommendation now, and so a strategy for addressing the science and/or retiring the technical risk is recommended.

Budgets

A prime task of this survey was to construct a program that is innovative and exciting yet also realistic and balanced in terms of the range and scale of federally supported activities. The committee chose for convenience and clarity to exhibit budgets in the form of unencumbered FY2010 dollars available for new initiatives, and it started by considering the agency-projected budgets.

National Aeronautics and Space Administration (NASA)

Although the NASA Astrophysics Division's annual budget has been as high as $1.7 billion in the past,[4] it is currently approximately $1.1 billion and projected to remain flat in real-year dollars through 2015, according to the President's FY2011 budget, and to remain flat thereafter according to NASA input to the committee. This implies a decrease in purchasing power over the decade at the rate of inflation. The committee concluded that this budget outlook allows very little in the way of new initiatives until mid-decade, by which time the James Webb Space Telescope (JWST) should be launched and opportunities for new funding wedges will open up. The committee also considered, as a basis for recommending a program, a more optimistic scenario in which the budget is flat over the decade in FY2010 dollars.

National Science Foundation (NSF)

Although the overall NSF budget is promised to "double," or increase by 7 percent each year for 10 years in real dollars, the agency input to the committee was that the Division of Astronomical Sciences (NSF-AST) portion of the budget would remain flat over the decade in FY2010 dollars (requiring approximately 3 percent growth per year in real-year dollars).[5]

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[4] Given here in FY2010 dollars; this was during the time of peak expenditure on the James Webb Space Telescope (from Paul Hertz, Chief Scientist, Science Mission Directorate, NASA, "Presentation to the Board on Physics and Astronomy," April 26, 2006, Washington, D.C., available at http://sites.nationalacademies.org/BPA/BPA_052067.

[5] Note that the NSF-AST budget did benefit from a one-time injection of $86 million in American Recovery and Reinvestment Act stimulus money in FY2009.

In this case, once existing obligations are honored and operations at the Atacama Large Millimeter/submillimeter Array (ALMA) and the Advanced Technology Solar Telescope (ATST) rise to the planned full levels by 2017, the committee found that the only way there can be any significant new initiative is through very large reductions in the funding for existing facilities and budget lines. Accordingly, the committee considered a more optimistic scenario that it believes to be justified given the success and promise of the NSF-AST program. In this scenario, NSF-AST participates fully in the aforementioned doubling of the NSF overall budget, and so its purchasing power would grow at 4 percent per year for 10 years. This scenario was used by the committee as a basis for building its recommended program.

In considering large ground-based construction projects, the committee assumed that the Major Research Equipment and Facilities (MREFC) line would be appropriate for new NSF-AST-supported projects to compete for—once ALMA is largely completed in 2012, and noting that $150 million of ATST funding is still planned to be drawn from the line until 2017. The committee also noted that in practice, an important limitation on the construction of new facilities under MREFC is the capacity of the NSF-AST budget to provide appropriate running costs, including operations, science, and upgrades, once construction is completed.

Department of Energy (DOE)

In seeking guidance on possible budget scenarios for activities that might be funded by DOE, some in partnership with the NSF Division of Physics (NSF-PHY), the committee looked to the 2009 report from the High Energy Physics Advisory Panel (HEPAP) and its Particle Astrophysics Scientific Assessment Group (PASAG) that reexamined current and proposed U.S. research capabilities in particle astrophysics under four budgetary scenarios.[6] The committee first adopted the more optimistic HEPAP-PASAG scenario, Scenario C, under which there is also a budget doubling as the basis for developing its program. It then considered the HEPAP-PASAG Scenario A, in which the total budget is constant in FY2010 dollars.[7]

[6] U.S. Department of Energy, *Report of the HEPAP Particle Astrophysics Scientific Assessment Group* (*PASAG*), October 23, 2009, available at http://www.er.doe.gov/hep/files/pdfs/ PASAG_Report.pdf.

[7] The HEPAP-PASAG report concluded that after allowance for a direct-detection dark matter program—which is not within the purview of this survey—Scenario A did not provide enough resources to support major hardware contributions to either LSST or JDEM (U.S. Department of Energy, *Report of the HEPAP Particle Astrophysics Scientific Assessment Group (PASAG)*, 2009.

SCIENCE OBJECTIVES FOR THE DECADE

The compelling science promise outlined in this report offers opportunities for making discoveries—both anticipated and unanticipated—for which the next decade will be remembered. The ingenuity and means are at hand to address the most promising and urgent scientific questions raised by the SFPs and summarized in Chapter 2, albeit on various timescales. The committee concluded that the way to optimize and consolidate the science return with the resources available is to focus on three broad science objectives for the decade—targets that capture the current excitement and scientific readiness of the field, and are motivated by the technical readiness of the instruments and telescopes required to pursue the science. These targets—Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes; New Worlds: Seeking Nearby, Habitable Planets; and the Physics of the Universe: Understanding Scientific Principles—are the drivers of the priority rankings of new activities and programs identified below. However, they form only part of the much broader scientific agenda that is required for a healthy program.

Cosmic Dawn: Searching for the First Stars, Galaxies, and Black Holes

Astronomers are on the threshold of finding the root of our cosmic origins by revealing the very first objects to form in the history of the universe. This step will conclude a quest that is akin to that of an anthropologist in search of our most ancient human ancestors. The foundations for this breakthrough are already in place with the current construction of ALMA, which will detect the cold gas and the tiny grains of dust associated with the first large bursts of star formation, and JWST, which will provide unparalleled sensitivity to light emitted by the first galaxies and pinpoint the formation sites of the first stars. This powerful synergy between JWST and ALMA applies not only to these first objects in the universe, but also to the generations of stars that followed them. The emergence of the universe from its "dark ages," before the first stars ignited, and the buildup of galaxies like our own from the first primordial seeds will be recorded. A staged development program is proposed beginning with the Hydrogen Epoch of Reionization Array-I (HERA-1) telescopes that are already under construction. The reionization of the primordial hydrogen by these first stars will be constrained by detections of cool gas from the dark ages with the first generation of HERA experiments. Much of what has already been learned has been informed by the results of theoretical investigations and sophisticated numerical simulations, and these are likely to play an increasingly important role in planning and interpreting future observations.

However, completing the record of galaxy formation, and understanding the composition and nature of these faint distant early galaxies, will require a new generation of large ground-based telescopes. A number of activities proposed to this survey would address this goal. For example, a submillimeter survey telescope such as CCAT (formerly the Cornell-Caltech Atacama Telescope) would be capable of identifying the dusty young galaxies that ALMA plans to study in detail. The 20- to 40-meter optical telescopes, known collectively as Giant Segmented Mirror Telescopes (GSMTs), that are planned for construction over the coming decade would render within spectroscopic reach the most distant objects imaged by JWST. A GSMT would allow scientists to determine the mass of the first galaxies and to follow the buildup of the first heavy elements made inside stars. As well as discovering how infant galaxies grow, astronomers would also understand how they shine and affect their surroundings through outflows of gas and ultraviolet radiation.

A major challenge to JWST and GSMT is to understand how and why the birth rate of stars grew, peaked when the universe was a few billion years old, and has now declined to only a few percent of its peak value. The star-formation history of the universe can also be tracked by gamma-ray observations made with the proposed Atmospheric Čerenkov Telescope Array (ACTA): as high-energy gamma rays from the distant universe are converted into electrons and positrons, they can indicate how much star formation there has been along the way.

The era when the strong ultraviolet radiation from the first stars ionizes the surrounding hydrogen atoms into protons and electrons is known as the epoch of reionization, which can be studied directly using sensitive radio telescopes. These should determine when reionization occurred, and they would inform the design of a proposed new telescope that would measure how the cavities of ionized hydrogen created by the light from the first generations of stars, galaxies, and black holes expand into the surrounding gas. In the long term, realization of the full potential of this approach would require in the following decade a detailed mapping of the transition in the early universe from protogalactic lumps of gas and dark matter into the first objects, a goal of the proposed worldwide effort to construct the low-frequency Square Kilometer Array (SKA-low) as discussed in the subsection “Radio, Millimeter, and Submillimeter” under “OIR and RMS on the Ground” in Chapter 3. Studies of the intergalactic medium, which accounts for most of the baryons in the universe, at more recent times could be transformed by an advanced UV-optical space telescope to succeed the Hubble Space Telescope (HST), equipped with a high-resolution UV spectrograph.

Galaxies are composed not just of stars orbiting dense concentrations of dark matter. They also contain gas and central, massive black holes. When the gas flows rapidly onto a central black hole, it radiates powerfully and a quasar is formed. Meanwhile the black hole rapidly puts on weight. It is already known from observations that these black holes can grow very soon after the galaxies form. However, the manner in which this happens is still a mystery. These accreting black holes can be seen back to the earliest times using the proposed space-based Wide-Field Infrared

Survey Telescope (WFIRST) and the International X-ray Observatory (IXO), and the masses of the black holes can be measured using a GSMT.

Simulations show that the first galaxies were likely relatively small and that the giant galaxies observed today grew by successive mergers. Observations of mergers should be possible using JWST, ALMA, WFIRST, and GSMT. As galaxies merge it is likely that their black holes merge as well. The proposed Laser Interferometer Space Antenna (LISA) mission will search for the signatures of these processes by scanning the skies for the bursts of gravitational waves produced during these early mergers when the black holes are relatively small. (LISA will not be sensitive to the mergers of more massive black holes.) An important part of the strategy is to search for associated flashes of electromagnetic radiation that are expected as part of these events. The proposed Large Synoptic Survey Telescope (LSST) will be ideally suited to this task and, working with a GSMT, should make it possible to pinpoint and date the sites of black hole merger events.

In summary, this survey committee recommends improving understanding of the history of the universe by observing how the first galaxies and black holes form and grow. To do so requires that current capabilities be supplemented with the priority ground- and space-based activities identified in this survey; see Box 7.1.

New Worlds: Seeking Nearby, Habitable Planets

The search for exoplanets is one of the most exciting subjects in all of astronomy, and one of the most dynamic, with major new results emerging even as this report was being written. As described in Chapter 2, an unexpectedly wide variety of types and arrangements of planets have been identified—even a few systems with some resemblance to our solar system. What has not been found yet is an Earth-like planet, that is, a terrestrial body with an atmosphere, signs of water and oxygen, and the potential to harbor life. This survey is recommending a program to explore the diversity and properties of planetary systems around other stars, and to prepare for the long-term goal of discovering and investigating nearby, habitable planets. This program is likely to be informed by theoretical calculations and numerical simulations.

Locating another Earth-like planet that is close enough for detailed study is a major challenge, requiring many steps and choices along the way. The optimum strategy depends strongly on the fraction of stars with Earth-like planets orbiting them. If the fraction is close to 100 percent, then astronomers will not need to look far to find an Earth-like planet, but if Earth-like planets are rare, then a much larger search extending to more distant stars will be necessary. With this information in hand, ambitious planning can begin to find, image, and study the atmospheres of those Earth-like planets that are closest to our own. Equally important to the characterization of an Earth-like planet is to understand such planets as a class.

BOX 7.1
Implementing a Cosmic Dawn Science Plan

- Carry out simulations and theoretical calculations to motivate and interpret observations aimed at understanding our cosmic dawn.
- Find and explore the epoch of reionization using hydrogen line observations starting with the **HERA** telescopes that are already under construction.
- Use **CCAT** to identify the best candidate young galaxies for study with submillimeter observations.
- Study these galaxies in detail using **ALMA**; in particular, monitor how fast the gas that they contain is being converted into stars.
- Use **JWST** to measure the rate at which stars are being formed out of gas, and understand their role in reionizing the universe.
- Use **GSMT** to study the early evolution of infant galaxies using optical and infrared spectroscopy.
- Use **GSMT** and **IXO** to monitor the exchange of gas between the galaxies and the surrounding intergalactic medium.
- Study the rate of formation and growth of black holes in the nuclei of young galaxies using **IXO** and **WFIRST**.
- Employ **LISA** to measure the rate at which young galaxies merge through observing powerful bursts of gravitational radiation produced during the coalescence of their nuclear black holes.
- Study the oldest stars in nearby galaxies using **GSMT.**

NOTE: ALMA, Atacama Large Millimeter/submillimeter Array; CCAT, formerly the Cornell-Caltech Atacama Telescope; GSMT, Giant Segmented Mirror Telescope; HERA, Hydrogen Epoch of Reionization Array; IXO, International X-ray Observatory; JWST, James Webb Space Telescope; LISA, Laser Interferometer Space Antenna; and WFIRST, Wide-Field Infrared Survey Telescope.

Although our own solar system has four such terrestrial bodies, the frequency of formation of terrestrial planets, mass distributions as a function of stellar mass, and orbital arrangements are not understood. Generating a census of Earth-like or terrestrial planets is the essential first step toward determining whether our own home world is a commonplace or rare outcome of planet formation.

We have various complementary means of building up a census of Earth-like planets. The ground-based radial velocity and transit surveys are most sensitive to large planets with small orbits, as is the Kepler satellite, although it should be capable of detecting Earth-size planets out to almost Earth-like orbits. Together these techniques will determine the probability of planets with certain orbital characteristics around different types of stars. To complete the planetary census, it will be necessary to use techniques that are sensitive to Earth-mass planets on large orbits. One such technique is called gravitational microlensing, whereby the presence of planets is inferred[8] through the tiny deflections that they impose on passing light rays from background stars. A survey for such events is one of the two main tasks of the proposed WFIRST satellite. Because microlensing is sensitive to planets of all masses having orbits larger than about half of Earth's, WFIRST would be able to complement and complete the statistical task underway with Kepler, resulting in an unbiased survey of the properties of distant planetary systems. The results from this survey will constrain theoretical models of the formation of planetary systems, enabling extrapolation of current understanding to systems that will still remain below the threshold of detectability.

However, in addition to determining just the planetary statistics, a critical element of the committee's exoplanet strategy is to continue to build the inventory of planetary systems around specific nearby stars. Therefore, this survey strongly supports a vigorous program of exoplanet science that takes advantage of the observational capabilities that can be achieved from the ground and in space.

The first task on the ground is to improve the precision radial velocity method by which the majority of the close to 500 known exoplanets have been discovered. The measured velocity amplitude of a star depends on the ratio of the planetary to the stellar mass, and on the distance from the star, with a Jupiter-mass body at 5 times the Earth-Sun distance from a Sun-like star producing a 12-meter-per-second signal and an Earth at the Earth-Sun location just a 6-centimeter-per-second signal. Improving the velocity precision will allow researchers to measure the masses of smaller planets orbiting nearby stars. Using existing large ground-based or new dedicated mid-size ground-based telescopes equipped with a new generation of high-resolution spectrometers in the optical and near-infrared, a velocity goal of 10 to 20 centimeters per second is realistic. This could allow detection of bodies twice or three times the mass of Earth around stars the mass of the Sun, and truly Earth-mass planets around stars a factor of two or three less massive than the Sun. The radial velocity technique is also of high value when paired with complementary techniques. For example, transits can determine planet sizes and, in combination with the mass found from another technique, yield clues regarding the bulk planetary compositions—just as we know that Earth is mostly rock and iron from its mass and size and a calculation of the average density. Improved precision astrometry and interferometric techniques that are sensitive to planets at larger separations could not only detect new Jupiter-class planets but also study known planetary systems in combination with radial velocity methods so as to resolve the ambiguity regarding true mass as distinct from the inferred minimum mass.

Success with endeavors to determine the solar neighborhood planetary census will be very important because knowing that Earth-mass planets exist around nearby stars will give much higher confidence that a future space mission to

[8] Neither the planet nor the planet host star is detected outside of the microlensing event.

investigate the atmospheres of extrasolar planets like Earth will succeed. A critical step along the way is a better understanding of the dusty disks surrounding stars, analogous to zodiacal dust found near Earth. Reflected diffuse exozodiacal light from these disks can make detection of the faint light from small Earth-like planets difficult. It is, therefore, important to quantify the prevalence and character of these dusty "debris" disks, and the period 2010-2015 will see the completion of ground-based mid-infrared interferometric instrumentation designed to study these phenomena.

It is also important to understand planetary systems in the process of formation to enrich and complement observations of the mature exoplanets. ALMA will revolutionize the imaging of protoplanetary disks at millimeter and submillimeter wavelengths and reveal important clues to the formation and evolution of their constituent planets. JWST and ground-based infrared telescopes equipped with adaptive optics to remove the twinkling due to Earth's atmosphere will provide spatially resolved multiwavelength images and spectra of light scattered from these disks with spatial resolution comparable to that of ALMA.

JWST, with its superb mid-infrared capability, will also use imaging and spectroscopy transit techniques to study the atmospheres of exoplanets, a science capability that has been amply demonstrated by the currently operating Spitzer Space Telescope. JWST will be a premier tool for studying planets orbiting stars that are smaller and cooler than the Sun. Also promising are improved techniques on the ground for direct imaging of planets using adaptive optics. New instrumentation is required as well as significant amounts of observing time (for example, on the Gemini telescopes and the privately operated facilities accessible through NSF's Telescope System Instrumentation Program). The proposed GSMTs could also play a crucial role in direct imaging studies with instruments suitably designed for this type of work.

In addition, enhancements to NASA Suborbital and Explorer programs could provide testbeds for the development of occulter techniques such as the use of star shades and coronagraphy, which are both immature, and technology development of astrometry and interferometry from space, so as to set the stage for an ambitious direct-detection mission in the 2020s. The scientific contributions and technology development in these various areas are described in detail elsewhere.[9]

The culmination of the quest for nearby, habitable planets is a dedicated space mission. The committee concluded that it is too early to determine what the design

[9] ExoPlanet Task Force of the Astronomy and Astrophysics Advisory Committee, *Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets*, National Science Foundation, Washington, D.C., 2008, available at http://www.nsf.gov/mps/ast/exoptf.jsp; Jet Propulsion Laboratory, *Exoplanet Community Report* (P.R. Lawson, W.A. Traub, and S.C. Unwin, eds.), JPL Publication 09-3, Pasadena, Calif., 2009.

of that space mission should be, or even which planet-detection techniques should be employed.[10] It is not even clear whether searches are best carried out at infrared, optical, or even ultraviolet wavelengths. This choice awaits the results of the observational studies just described, alongside a vigorous and adaptive program of theoretical and laboratory astrophysics investigations that will inform scientists about the diversity of exoplanet atmospheres. Although the case is compelling for technology development for a future space mission beginning early, its emphasis may shift as new discoveries from the ground and space materialize. If progress is sufficiently rapid by mid-decade, then a decadal survey implementation advisory committee (as discussed in Chapter 3) could determine whether a more aggressive program of technology development should be undertaken, possibly including steps toward a technology down-select and a focus on key elements. Either way, decisions on significant, mission-specific funding of a major space mission should be deferred until the 2020 decadal survey, by which time the scientific path forward should be well determined.

In summary, exoplanet astronomy is one of the most rapidly developing and unpredictable fields in modern astronomy. Both the statistical investigations of Kepler and WFIRST, and the location of specific, nearby, potentially habitable Earth-like planets under a strong yet flexible program of ground-based research, are recommended. This combined approach will allow new techniques to be devised and surprising discoveries to be made during the coming decade; see Box 7.2.

The Physics of the Universe: Understanding Scientific Principles

Astronomy has made many contributions to our understanding of basic physics and chemistry, ranging from Newton's laws of gravitation to the discovery of helium, from providing much of the impetus for understanding nuclear physics to discovering new types of molecules unique to interstellar environments. Perhaps the best-developed recent example has come from high-precision tests of the theory

[10] In considering possible exoplanet missions for the next decade, the committee gave serious consideration to SIMLite but decided against recommending it. SIMLite is technically mature and would provide an important new capability (interferometry). Through precision astrometry it could characterize the architectures of 50 or so nearby planetary systems, provide targets for future imaging missions, and carry out other interesting astrophysics measurements. However, the committee considered that its large cost (appraised by the CATE process at $1.9 billion from FY2010 onward) and long time to launch (estimated at 8.5 years from October 2009) make it uncompetitive in the rapidly changing field of exoplanet science. The planetary architecture science can be more efficiently carried out by the committee's exoplanet strategy involving Kepler, WFIRST, and the ground-based program. The role of target-finding for future direct-detection missions, one not universally accepted as essential, can be done at least partially by pushing ground-based radial velocity capabilities to a challenging but achievable precision below 10 centimeters per second. Finally, the ancillary astrophysics promised by SIMLite was not judged to be competitive.

BOX 7.2
Implementing a New Worlds Science Plan

- Locate the prime targets for hosting habitable, terrestrial planets among our closest stellar neighbors.
- Carry out a focused program of computation and theory to understand the architectures of planets and disks.
- Use the **Kepler** transit survey to measure the probability that a solar-type star has a massive terrestrial companion, and that a red star harbors an Earth-like planet.
- Perform a microlensing survey from space using the recommended **WFIRST** to characterize in detail the statistical properties of habitable terrestrial planets.
- Improve radial velocity measurements on existing ground-based telescopes to discover planets within a few times the mass of Earth as potential targets for future space-based direct-detection missions.
- Use ground-based telescopes, including **ALMA**, AO-equipped optical-infrared telescopes such as **GSMT**, and mid-infrared interferometry, or space-based Explorers, to characterize the dust environment around stars like the Sun, so as to gauge the ability of future missions to directly detect Earth-size planets in orbits like that of our own Earth.
- Use **JWST** to characterize the atmospheric or surface composition of planets within a few times the size of Earth, orbiting the coolest red stars. These are the planets that might be discovered by ground- and possibly space-based surveys.
- Follow up nearby systems discovered by **Kepler.**
- Assess habitability by using **IXO** to characterize the frequency and intensity of flares on host stars.
- Use **ALMA** and **CCAT** to seek biogenic molecules thought to be precursors to life.
- Develop the technology for an ambitious space mission to study nearby Earth-like planets.

NOTE: ALMA, Atacama Large Millimeter/submillimeter Array; CCAT, formerly the Cornell-Caltech Atacama Telescope; IXO, International X-ray Observatory; JWST, James Webb Space Telescope; Kepler; and WFIRST, Wide-Field Infrared Survey Telescope.

of gravity encompassed by Einstein's theory of general relativity. However, these tests have been restricted to the situations where gravity is weak, and the strong field expression of the theory still remains to be tested. The discovery of dark energy and dark matter and the amassed evidence that is at least consistent with the predictions of the theory of inflation present two more examples where carefully controlled astronomical measurements contribute to current understanding of fundamental physics. Here the committee highlights these three topics, mindful of a range of other such opportunities, mentioned below.

The standard model of cosmology developed in the 1980s and 1990s has been amply confirmed over the past decade by observations of the cosmic microwave background (CMB) using ultrasensitive radio telescopes on the ground, balloons, and spacecraft. With a combination of these and other observations, astrophysicists have shown that the geometry of space is approximately flat, that the age of the universe is 13.7 billion years, and that there is nearly five times as much matter in a dark, invisible form as in normal matter that can turn into visible stars. The past decade also saw strong affirmation of the remarkable discovery that the expansion of the universe is accelerating.

We can now say that there is a ubiquitous and ethereal substance called dark energy that is expanding the fabric of space between the galaxies at ever faster speeds and that accounts for 75 percent of the mass-energy of the universe today. The effects are so tiny on the scale of an experiment on Earth that the only way forward is to use the universe at large as a giant laboratory.

Two complementary approaches to understanding dark energy have been considered by this survey: one on the ground and the other in space. On the ground, the proposed LSST would provide optical imaging of brighter galaxies over half the sky every few days. It would build up measurements of galaxy images that are distorted by (weak) gravitational lensing and detect many relatively nearby supernovae. From space, the proposed WFIRST would produce near-infrared images of fainter galaxies over smaller areas and observe distant supernovae. It would also provide near-infrared spectroscopy for sensitive baryon acoustic oscillation measurements. What has become clear over the past few years is that instead of just considering dark energy in different regimes, LSST and WFIRST will actually be quite synergistic, and observations from one are essential to interpreting the results of the other. In particular, by working together, they would provide the powerful color information needed for redshift[11] estimation. The properties of dark energy would be inferred from the measurement of both its effects on the expansion rate and its effects on the growth of structure (the pattern of galaxies and galaxy clusters in the universe). In doing so it should be possible to measure deviations from a cosmological constant[12] larger than about a percent. Massively multiplexed spectrographs in intermediate-class and large-aperture ground-based telescopes would also play an important role.

Second, and most remarkably, it is now possible to contemplate observing the earliest moments of the universe. Another source of gravitational radiation may be the most intriguing of all. The patterns in the CMB are theoretically consistent with what could have been laid down during the first instants after the big bang during an

[11] Spectral lines in the electromagnetic radiation emitted by an object are shifted to longer (“redder”) wavelengths if the object is moving away from an observer. The greater the redshift, the more distant the object.

[12] A term in Einstein’s general relativity theory that represents the density and pressure associated with empty space, which counteracts the gravitational pull of matter.

epoch of rapid expansion, called inflation. The recently launched Planck satellite will produce higher-resolution, all-sky CMB temperature and polarization maps at many frequencies. Complementary observations from the ground will look at patches of the sky with fine angular resolution. These experiments will be able to compare the temperature fluctuations on a range of scales, from those so small that they will grow into only a small group of galaxies today, to the largest-scale fluctuations observable on the whole sky, which will allow scientists to see if the fluctuations are truly random or instead non-Gaussian, as some theories suggest. However, the most ambitious goal of all is to try to detect a particular pattern in the polarization—called B-modes—that is caused by very long wavelength gravitational radiation that would be created at the time of inflation. The B-modes are a window allowing us to peer far back beyond the screen of the CMB into the period of inflation.

The convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery. The strength of the associated fluctuations, now constrained to less than 20 percent, should be measurable by upcoming telescopes at a level as low as 20 times weaker than the current limit. If these fingerprints of inflation are detected, then a decadal survey implementation advisory committee (DSIAC) (as discussed in Chapter 3) could determine whether a technology development program should be initiated with a view to flying a space microwave background mission during the following decade that would be capable of improving the accuracy by a further factor of 10 and elucidating the physical conditions at the end of inflation.

Third, an inescapable consequence of general relativity is the existence of black holes. Once mere conjectures, black holes are now known to be very common. They are found at the centers of normal galaxies like our own Milky Way and as companions to normal stars transferring mass to their neighbors through winds. Gas close to a black hole radiates X-rays prodigiously and offers a quantitative observational test of relativistic theory that would be possible to conduct with the proposed sensitive International X-ray Observatory, IXO. Another general property of black holes is that they create jets of hot plasmas that move at speeds very close to that of light and create intense beams of radiation from the longest radio wavelengths to the highest gamma-ray energies. The proposed Advanced Čerenkov Telescope Array (ACTA) will use high-energy gamma-ray observations to probe the properties of black holes.[13]

[13] The committee also considered a proposed black hole finder mission called the Energetic X-ray Imaging Survey Telescope (EXIST). This was recommended by AANM and further considered by the NRC's Beyond Einstein Program Advisory Committee (NRC, *NASA's Beyond Einstein Program: An Architecture for Implementation*, The National Academies Press, Washington, D.C., 2007). While it would address important science goals, the high estimated cost of $2.4 billion, well over 10 times the cost indicated in the 2001 decadal survey, AANM, ruled it out for further consideration, and it is no longer recommended.

General relativity also predicts the existence of gravitational waves, which travel at the speed of light. Our understanding of gravity waves has improved recently to include solving the relevant equations when gravity is strong, thanks to theoretical breakthroughs in numerical relativity. Astrophysicists now have the ability, in principle, to calculate the complete waveforms that should be observed from most types of powerful sources. To date, the effects of gravitational radiation have been observed only indirectly using sensitive measurements of spinning magnetized neutron stars, or pulsars, when they have orbiting stellar companions. These measurements are consistent with the theory, but the goal of detecting gravitational waves directly has not yet been met.

The first of these ripples in space-time likely to be detected will probably arise from the death spiral of a binary neutron star. Sustained international investments over the last 20 years would culminate with the mid-decade completion of the advanced Laser Interferometer Gravitational Wave Observatory (LIGO), which should make regular detections of this and many other types of sources at relatively short wavelengths.

However, the ultimate goal is to measure the full gravitational waveform for direct comparison with theoretical expectations. To accomplish this, measurements are needed at longer wavelengths to test the theory by means of sustained observations of merging black holes. This is the primary purpose of LISA, from which the signals will be of such high quality that the full gravitational waveform can be measured. A key recent development has been the solution of the theoretical problem of calculating the signals that should be seen from merging black holes. The results will test current understanding of general relativity and provide accurate measurements of the spin and mass of the merging black holes. These are vital parameters for understanding the origins and growth of the most massive black holes in the universe. We should also witness the capture of stars by massive black holes with signals of such long duration and fidelity that the space-time of the black hole can be directly mapped.

In summary, this survey recommends supplementing the current ability to use the universe as a giant cosmic laboratory to study dark energy, inflation, and black holes. Success in this endeavor would provide critical constraints on the laws of physics and the behavior of the universe that would inform efforts to realize a unification of gravity and quantum mechanics through string theory or other approaches; see Box 7.3.

THE LARGER SCIENCE PROGRAM

The three primary science objectives played a large role in motivating the difficult prioritization choices the committee had to make. They represent goals against which progress and prospects for individual facilities can be assessed over

BOX 7.3
Implementing the Physics of the Universe Science Plan

- Continue theoretical investigations of models of dark energy and inflation.
- Combine observations with **LSST**, **WFIRST**, and **GSMT** to measure nearby distant supernova explosions and map the expansion of the universe.
- Use **WFIRST** and **LSST** to find traces of the residual sound waves produced in the first moments of the universe by mapping the distribution of galaxies and making an independent measurement of the rate of expansion of the universe.
- Measure the shape distortions of distant galaxies caused by weak gravitational lensing, using **WFIRST** and **LSST** to help characterize the properties of dark energy.
- Find and study distant clusters of galaxies to measure the rate of growth of structure in the universe using **IXO** and microwave background observations.
- Complete the theoretical calculations of waveforms from merging black holes.
- Detect bursts of gravitational radiation from merging black holes using **LISA**.
- Study the epoch of inflation by measuring the imprint of gravitational radiation on the cosmic microwave background.
- Observe x rays from gas orbiting close to the event horizon of black holes using **IXO** and relativistic jets produced by black holes using **ACTA**.
- Gather indirect evidence using **ACTA** to show that dark matter comprises a new type of elementary particle by detecting the gamma rays it may emit.

NOTE: ACTA, Atmospheric Čerenkov Telescope Array; GSMT, Giant Segmented Mirror Telescope; IXO, International X-ray Observatory; LISA, Laser Interferometer Space Antenna; LSST, Large Synoptic Survey Telescope; and WFIRST, Wide-Field Infrared Survey Telescope.

the coming decade. However, there is much other science outlined in Chapter 2 that is also important and timely. The program of activities proposed as a result of Astro2010 also advances this larger research program, cast here as in Chapter 2 in terms of cross-cutting themes in astronomy and astrophysics research.

Discovery

Anticipating research results in a rapidly changing field is demonstrably hard, and comparisons between expectations and actual scientific results are both humbling and exhilarating. For example, when the Keck Observatory, the Hubble Space Telescope, and the Spitzer Space Telescope were designed astronomers had no evidence that there were planets around nearby stars or that gamma-ray bursts were at cosmological distances. These observatories, both independently and when used together to study the same objects, have been invaluable in advancing knowledge in unpredictable directions. Astronomy is still as much based on discovery as it is on predetermined measurements.

The committee emphasizes that its recommended activities have the capacity to find the unexpected and the versatility to engage in follow-up observations. For example, WFIRST and LSST as recommended here would open up the time domain to reveal remarkable surprises and enable the creation of massive databases that will be mined for decades. It would be unprecedented in the history of astronomy if the gravitational radiation window being opened up by LISA does not reveal new, enigmatic sources. Most of the observing time on GSMT, IXO, and ACTA would not be allocated according to a preordained strategy; rather, individuals and teams would compete for time to explore new scientific approaches and pursue recent discoveries. The broadly based and balanced suite of facilities that are recommended is flexible and resilient enough to make and exploit the many unanticipated and thrilling discoveries that are sure to come during the coming decade. Many of the most fundamental advances in astronomy and astrophysics have resulted from theoretical discoveries that could not have been anticipated in any planning exercise—the theory of inflation is one example—but the recommended Theoretical and Computational Network program and augmentations in individual investigator grants programs at NSF and NASA will help to enable such discoveries.

Origins

Understanding the dramatic evolution of galaxies over cosmic time through observations is a key part of the committee's recommended science program. Following the growth of cosmic structure and learning empirically how the dark and luminous matter are connected is a major science goal for GSMT, which, with its superb spectroscopic reach, would be able to measure redshifts and thus infer distances all the way from our local neighborhood to the epoch of reionization and monitor the buildup of mass and the rise and fall of star formation at visual wavelengths. Meanwhile CCAT would provide the submillimeter perspective on the history of star formation over cosmic time. (See Figure 7.2 for an illustration of the complementarity.) The "fossil record" of how our Milky Way galaxy was assembled can be traced by studying resolved stellar populations with LSST and JWST, and by using the adaptive optics capability on GSMT. GSMT would also be able to perform exquisite spectroscopy of the most ancient, nearby stars. In the next decade, large-scale numerical simulations of the formation and evolution of galaxies should achieve the spatial resolution and physical realism necessary to interpret these observations successfully and to tell the story of how our galaxy was born.

Our understanding of star formation under a wide variety of physical conditions will benefit from extensive surveys of the giant molecular clouds within which stars form. ALMA will and CCAT would be major tools for this exploration.

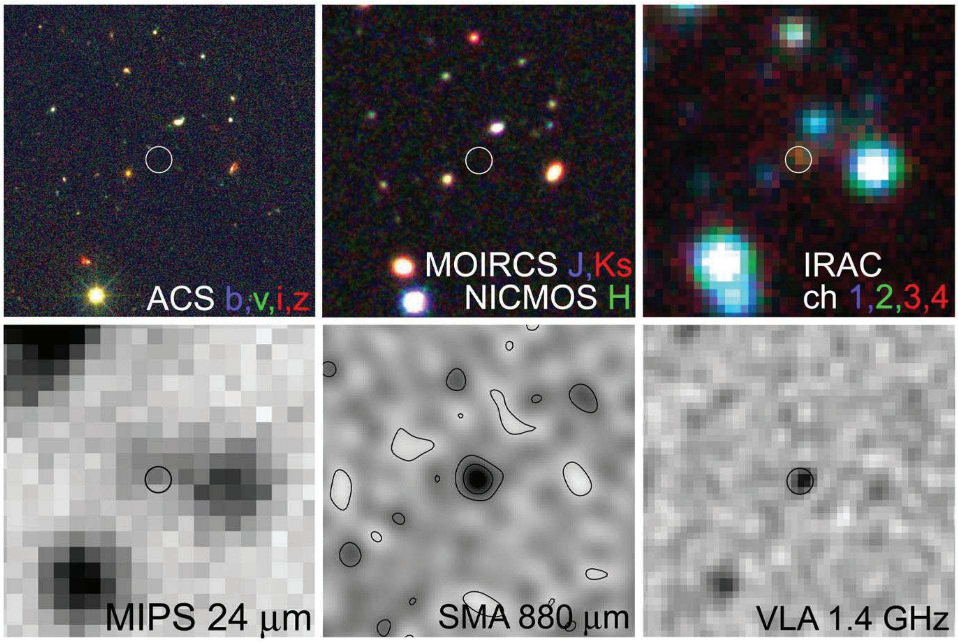

FIGURE 7.2 Multiwavelength images of high-redshift source GOODS 850-5 showing the complementarity of multiwavelength data and the promise of a future GSMT/JWST/CCAT/ALMA combination for studies of early galaxies. SOURCE: W.-H. Wang, A.J. Barger, and L.L. Cowie, Ultradeep near-infrared observations of Goods 850-5, Astrophysical Journal 690:319, 2009. Reproduced by permission of AAS.

Complementary studies of the young stars spawned in these molecular regions will require infrared surveys with high angular resolution both in our galaxy and in the neighboring galaxies the Magellanic Clouds, using JWST in space and GSMT equipped with adaptive optics on the ground.

Since solar flares create many cosmic rays that can cause mutations of genetic material, understanding these flares is important for understanding the chances of a planet being habitable. Flares on the more numerous low-mass, cool stars may preclude some forms of life on orbiting planets already known and to be discovered. Studying flares from the Sun using optical techniques with ATST—and at radio frequencies by using the proposed Mid-Scale Innovations Program candidate, the Frequency Agile Solar Radiotelescope (FASR)—as well as studying stellar flares in far-off planetary systems using the proposed IXO, could advance our understanding of planetary habitability.

Understanding the Cosmic Order

The critical constituents of galaxies—dark matter, stars, gas, dust, and supermassive black holes—are strongly coupled to one another. The program recommended here will allow major progress in our understanding of this cosmic order. Large multiobject spectroscopic surveys with new instruments would measure the stellar populations and the internal motions of thousands of distant galaxies in a single observation. High-angular-resolution optical and near-infrared integral-field-unit spectrographs on intermediate-class and large-aperture ground-based telescopes would trace in detail the internal velocity fields of galaxies. Meanwhile, while JWST will provide observations on the assembly of galaxies over cosmic time, IXO would obtain X-ray observations of the warm and hot gas in the dark matter halos that surround galaxies.

High-mass stars embedded in dense gas within galaxies can be inventoried with CCAT and studied in detail with ALMA. These stars are thought to be the main agents for injecting mass and energy into the interstellar medium and for driving galactic outflows. They do this through powerful stellar winds and supernova explosions, both of which are also responsible for accelerating cosmic rays and amplifying magnetic fields. The proposed ACTA facility will advance understanding of the mechanisms involved. The cycling of gas from galaxies to the surrounding intergalactic medium and back again could also be studied with a GSMT telescope, using high-resolution optical spectra to study gas absorption lines highlighted by background quasars along many sight-lines, but a future UV space mission will be needed for a complete inventory. This program of observations will move the subject of galaxy evolution from one dominated largely by surveys to one of integrated measurements of the buildup of dark matter, gas, stars, metals, and structure over cosmic time. These observations will lay the foundation for the ultimate aim of a complete ab initio theory of galaxy formation and evolution.

Understanding of the structure and evolution of stars is the foundation on which the knowledge of galaxies and the rest of the universe is built. ATST will provide tools for the study of solar (and hence stellar) rotation and magnetic fields. The time-domain information obtained from LSST would provide an unprecedented view of magnetic activity in other stars. LSST would also yield a large sample of Type Ia supernovae that could be followed up immediately by a GSMT in order to identify the progenitor stars and better understand the physical processes involved in their explosions. Likewise LSST would detect many Type II supernovae and find new types of rare or faint outcomes of massive-star evolution that have never been seen before. Key properties of compact stellar remnants such as neutron stars will be measured in new radio pulsar surveys that are less biased against detecting the fastest-rotating pulsars.

The study of the circumstellar disks out of which planets form will benefit greatly from the high spatial resolution of GSMT, fitted with high-contrast instrumentation so that the faint disks do not get lost in the glare of their parent stars, and there is complementary coverage of wavelengths with JWST and ALMA. Resonant structures and gaps within a disk that may be caused by gravitational perturbations due to planets will be imaged in optical, infrared, and submillimeter radiation, allowing a complete picture of the structure and composition of these disks to be derived.

Frontiers of Knowledge

The hunt is on to elucidate the nature of dark matter first identified by astronomers more than 70 years ago. If it comprises supersymmetric particles, then there are hopes that they will be seen directly at particle accelerators like the Tevatron and the Large Hadron Collider (LHC). They may also be seen directly at one of the many different types of underground detectors being built. However, it is also possible that they will be identified indirectly by the gamma rays that are produced through annihilation or decay processes in distant dark matter concentrations. A new ACTA would be roughly 10 times more sensitive than existing facilities and able to further constrain the nature of dark matter. ACTA could also check that the highest-energy photons do, indeed, travel at the speed of light.

Another potential contribution to fundamental physics will come from microwave background observations using future CMB telescopes combined with probes of structure formation, which can provide an upper limit to the sum of the masses of the three flavors of neutrino with higher sensitivity than can be done with ongoing laboratory experiments. More detailed information may also emerge on the individual particle masses.

A third possible contribution is to nuclear physics. Neutron stars can be thought of as giant atomic nuclei, and understanding how their radii change with the mass is of fundamental importance for nuclear physics and complements what is being learned from collisions of heavy ions. These astronomical measurements are becoming possible using radio and X-ray telescopes.

Turning to chemistry, with the advent of ALMA and CCAT in particular, an explosion in the variety of detected interstellar and circumstellar molecules is expected. A better understanding of the chemistry of these molecules will provide new information about stellar evolution and galaxy formation and evolution.

RECOMMENDED PROGRAM OF ACTIVITIES

On the basis of the input from the community, the priority science identified by the SFPs, the prioritized conclusions of the PPPs, and the results of the independent cost appraisal and technical evaluation process, the committee developed the ranked program described below for ground-based and spaced-based astronomy in the United States. In each category, the discussion proceeds with ranked large and ranked medium priorities followed by unranked smaller priorities. A large space activity is one with total cost estimated to exceed $1 billion; a medium space activity is one with total cost estimated to range from $0.3 billion to $1 billion. A large ground-based activity is one with total cost of construction and acquisition of capital assets estimated to exceed the threshold for the NSF's MREFC program (currently $135 million in FY2010 for projects from the Directorate for Mathematical and Physical Sciences); a medium ground-based activity is an initiative for which the total cost would fit into the Mid-Scale Innovations Program range, $4 million to $135 million as defined by this committee. The committee has not ranked the core-sustaining activities described in Chapter 5 except in the sense that it has recommended funding augmentations to some relative to the current levels of support. The committee's priorities have varying degrees of relevance to DOE, NASA, and NSF, given that some projects are envisioned as being supported by more than one agency.

Recommendations for New Space Activities—Large Projects

Priority 1 (Large, Space). Wide-Field Infrared Survey Telescope (WFIRST)

WFIRST[14] is a wide-field-of-view near-infrared imaging and low-resolution spectroscopy observatory that will tackle two of the most fundamental questions in astrophysics: Why is the expansion rate of the universe accelerating? And are there other solar systems like ours, with worlds like Earth? In addition, WFIRST's surveys will address issues central to understanding how galaxies, stars, and black holes evolve. WFIRST will carry out a powerful extrasolar planet search by monitoring a large sample of stars in the central bulge of the Milky Way for small deviations in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters. To measure the properties of dark energy, WFIRST will employ three different techniques: it will image about 2 billion galaxies and carry out a detailed study of weak lensing that will provide distance and rate-of-growth information; it will measure spectra of about 200 million galaxies in order to monitor distances and expansion rate using

[14] Adopted by the committee, the name WFIRST was suggested by the Electromagnetic Observations from Space (EOS) Program Prioritization Panel when the panel recognized a compelling opportunity in three separate projects proposed to Astro2010 (JDEM-Omega, the Microlensing Planet Finder, and the Near-Infrared Sky Surveyor), which, together, form the highest-priority activity.

baryon acoustic oscillations; and finally, it will detect about 2,000 distant supernova explosions, which can be used to measure distances. WFIRST provides the space-unique measurements that, combined with those from LSST (the committee's highest-priority ground-based project), are essential to advance understanding of the cause of cosmic acceleration. In addition, WFIRST will survey large areas of sky to address a broad range of Astro2010 science questions raised to advance understanding of phenomenon ranging from the assembly of galaxies to the structure of the Milky Way. WFIRST will also offer a guest investigator program supporting both key projects and archival studies to address a broad range of astrophysical research topics.

WFIRST is a 1.5-meter telescope that will orbit the second Lagrange point (L2), 1.5 million kilometers from Earth. It will image the sky at near-infrared wavelengths and perform low-resolution infrared spectroscopy. The spacecraft hardware that was used as a template for studying WFIRST was one of two JDEM proposals submitted to the committee—the JDEM-Omega proposal (Figure 7.3). This was used as a basis for the cost appraisal and technical evaluation. Undoubt-

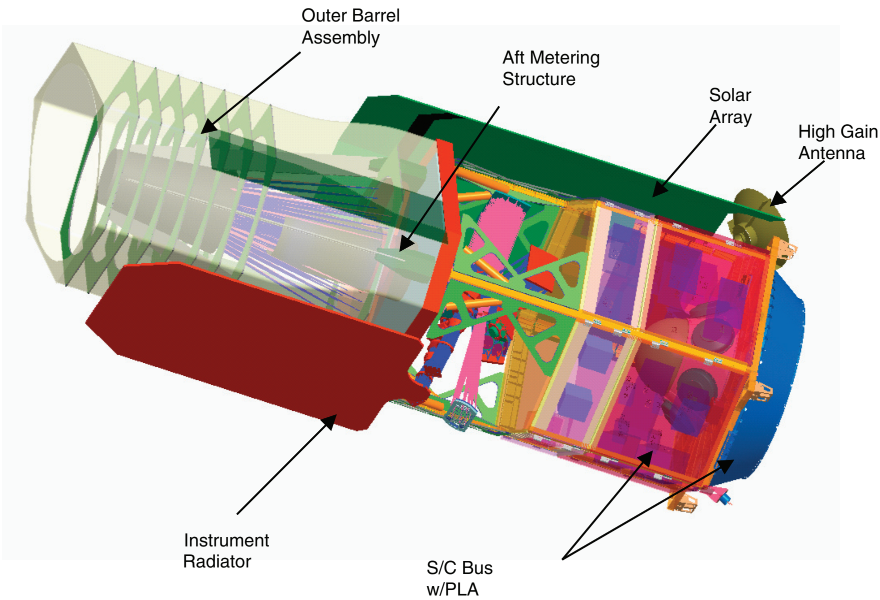

FIGURE 7.3 An infrared telescope with a three-mirror design, WFIRST will have HgCdTe detectors with 144 megapixels in total and angular resolution of 200 milliarcseconds. The sensitivity should be about 200 nJy or 26th magnitude, enabling shape measurements and photometric redshifts to a depth of 100,000 galaxies per square degree over half the sky. Spectroscopy will be achieved with a grism or prism and will rely mainly on measurement of the "H alpha" line of hydrogen out to a redshift of about 1.8. SOURCE: JDEM Project, NASA-GSFC.

edly, design improvements are possible, but its capabilities are essentially identical to those envisaged for WFIRST.

In a 5-year baseline mission, its observations would emphasize the planet census and dark energy measurements, while accommodating a competed general investigator program for additional surveys that would exploit WFIRST's unique capabilities using the same observation modes. The powerful astronomical survey data collected during all of the large-area surveys would be utilized to address a broader range of science through a funded investigator program. An extended mission, subject to the usual senior review process, could both improve the statistical results for the main science drivers and broaden the general investigator program.

The independent cost and readiness assessment found that WFIRST is based on mature technologies and has relatively low technological risk. The three primary challenges identified—achieving the image quality over the focal plane necessary for studies of weak lensing, providing adequate telemetry bandwidth from L2, and designing a focal plane that would jointly optimize the exoplanet and dark energy science—do not present high risk. At the 70 percent confidence level the appraised cost is $1.6 billion, with a time from project start to launch of 82 months. The enhanced observing plan relative to JDEM, to include both microlensed planet and dark energy surveys, is not expected to be a serious cost or schedule driver. The additional cost of a guest investigator program was not included in the cost and risk assessment. The committee considers the general investigator program to be an essential element of the mission, but firmly believes it should not drive the mission hardware design or implementation cost. NASA should consider creative ways to enable the most flexible possible general investigator program consistent with the current spacecraft and instrument suite.

WFIRST employs the JDEM-Omega design, conceived and developed in a collaboration between DOE and NASA. Other versions of a JDEM mission have been endorsed in two previous NRC reports.[15] Much progress has been made in defining the scientific objectives, and a variety of mission concepts have been discussed and compared. This continuing interagency collaboration on the proposed WFIRST is important both scientifically and technically. In addition, the committee is aware that plans are now underway in Europe for a similar mission, Euclid, which has many of the same scientific goals as WFIRST. Euclid is also in its definition phase and is competing with PLATO and Solar Probe for one of the two M-class launch slots of the European Space Agency's (ESA's) Cosmic Vision program, now scheduled for 2017 and 2018. There have been discussions between the U.S. agencies and ESA about mounting a joint mission, which could be a positive development if it

[15] National Research Council, *Connecting Quarks with the Cosmos* (2003) and *NASA's Beyond Einstein Program: An Architecture for Implementation* (2007), The National Academies Press, Washington, D.C.

leads to timely execution of a program that fully supports all of the key science goals of WFIRST (planet microlensing, dark energy science, and guest observer investigations) and leads to savings overall. It is expected that the United States will play a leading role in this top-priority mission.

WFIRST addresses fundamental and pressing scientific questions and contributes to a broad range of astrophysics. It complements the proposed ground-based program in two key science areas: dark energy science and the study of exoplanets. It is an integral part of coordinated and synergistic programs in fields in which the United States has the leading role. It also presents opportunities for interagency and perhaps international collaboration that will tap complementary experience and skills. It also presents relatively low technical and cost risk, making it feasible to complete within the decade, even in a constrained budgetary environment. For these reasons it is the top-priority recommendation for a space-based initiative. A 2013 new start should enable launch in 2020.

Priority 2 (Large, Space). Explorer Program

The Explorer program's Small Explorer (SMEX) and Medium-scale Explorer (MIDEX) missions, developed and launched on few-year timescales, enable rapid response to new discoveries and provide platforms for targeted investigations essential to the breadth of NASA's astrophysics program. From the WMAP MIDEX measurements of the age and content of the universe accomplished through its mapping of the cosmic microwave background (see Figures 2.4 and 2.5 in Chapter 2), to the GALEX SMEX contributions to understanding of the evolution of galaxies, Explorers are on the forefront of scientific discovery (Figure 7.4). With multiple missions launched per decade for a cost substantially less than that of a single flagship mission, the Explorer program is unique in the world for its versatility and scientific return for the investment. The Explorer program also offers highly leveraged Missions of Opportunity (MoOs), which enable U.S. scientists to make scientific and hardware contributions to non-NASA missions, and which provide a mechanism to develop large suborbital experiments.

The frequent opportunity to deploy SMEX (currently $160 million) and MIDEX (currently $300 million) experiments on timescales significantly less than a decade has enabled the United States to seize scientific opportunities, exploit new technologies and techniques, and involve university groups, including students and postdoctoral scholars, in significant development roles. As described in Chapter 5, this capability is essential to training the next generation of scientists and engineers. However, the program's original intent to deploy an astrophysics SMEX and a MIDEX mission every other year is not being met, given that the launch rate has fallen dramatically to just two per decade. The Announcements of Opportunity

(AOs) have been so infrequent that the ability to partner with foreign missions has been compromised, and resources have been insufficient to select suborbital platforms, which can be critical to advancing key science goals.

The committee therefore recommends, as its second priority in the large category of space-based projects, that NASA should support the selection of two new astrophysics MIDEX missions, two new astrophysics SMEX missions, and at least four astrophysics MoOs over the coming decade. AOs should be released on a predictable basis as close to annually as possible, to facilitate Missions of Opportunity. Further, the committee encourages inclusion of suborbital payload selections, if they offer compelling scientific returns. To accommodate this plan, an annual budget increase would be required for the astrophysics portion of the program from its current average value of about $40 million per year to a steady value of roughly $100 million by 2015. The placement of this recommendation in the large category reflects the decade's total cost of the program including the augmentation and the committee's view that expanding the Explorer program is essential to maintaining the breadth and vitality of NASA's astrophysics program. This is especially true in an era where budgetary constraints limit the number of flagship missions that can be started.

Priority 3 (Large, Space). Laser Interferometer Space Antenna (LISA)

LISA is a gravity wave observatory that would open an entirely new window in the universe (Figure 7.5). Using ripples in the fabric of space-time caused by the motion of the densest objects in the universe, LISA will detect the mergers of black holes with masses ranging from 10,000 to 10 million solar masses at cosmological distances, and will make a census of compact binary systems throughout the Milky Way. LISA's measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies. LISA also is expected to detect signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes. Detection of such objects would provide exquisitely precise tests of Einstein's theory of gravity. There may also be waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings.

Using three "drag-free" spacecraft launched into an equilateral triangular configuration in an Earth-trailing orbit, LISA would explore the low-frequency (0.1 to 100-mHz) portion of the gravitational wave spectrum, observable only in space, to achieve its scientific objectives. The sides of the triangle are 5 million kilometers, and the "laser-connected" spacecraft would measure their separations to an accuracy enabling detection of tens of picometers relative motions induced by passing gravitational waves. The mission lifetime is planned as 5 years.

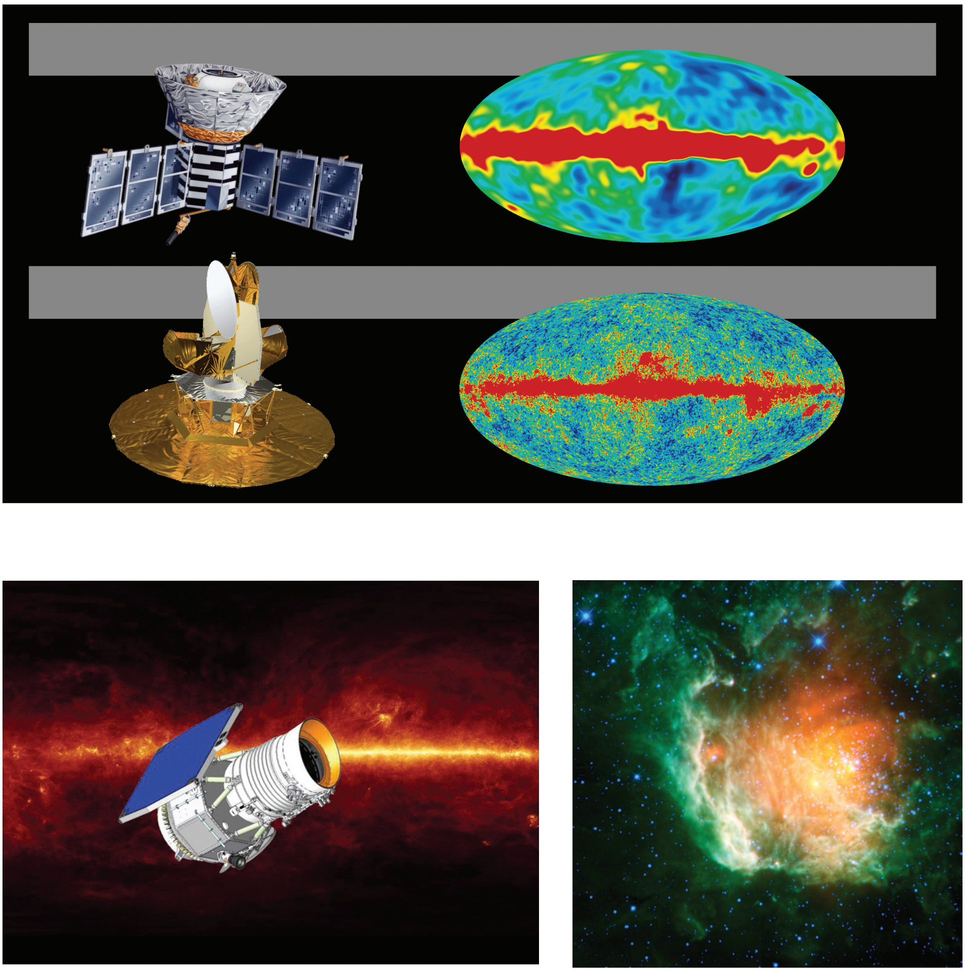

FIGURE 7.4 Science accomplishments from competitively selected astrophysics Explorer SMEX and MIDEX missions launched since 2000. In addition the Explorer program supported a Mission of Opportunity (MoO) contribution to Suzaku and will launch two new SMEX X-ray missions, NuSTAR and GEMS, in 2012 and 2014, respectively. A MoO contribution of an X-ray spectrometer to the Japanese Astro-H is planned for 2014. SOURCE (*paired images, clockwise from upper left*): (1) WMAP MIDEX—NASA/WMAP Science Team; (2) Swift MIDEX—Orbital Sciences Corporation; NASA E/PO, Sonoma State University, and Aurore Simonnet; (3) GALEX SMEX—NASA/JPL-Caltech; and (4) WISE MIDEX—NASA/JPL-Caltech/WISE Team; NASA/JPL-Caltech.

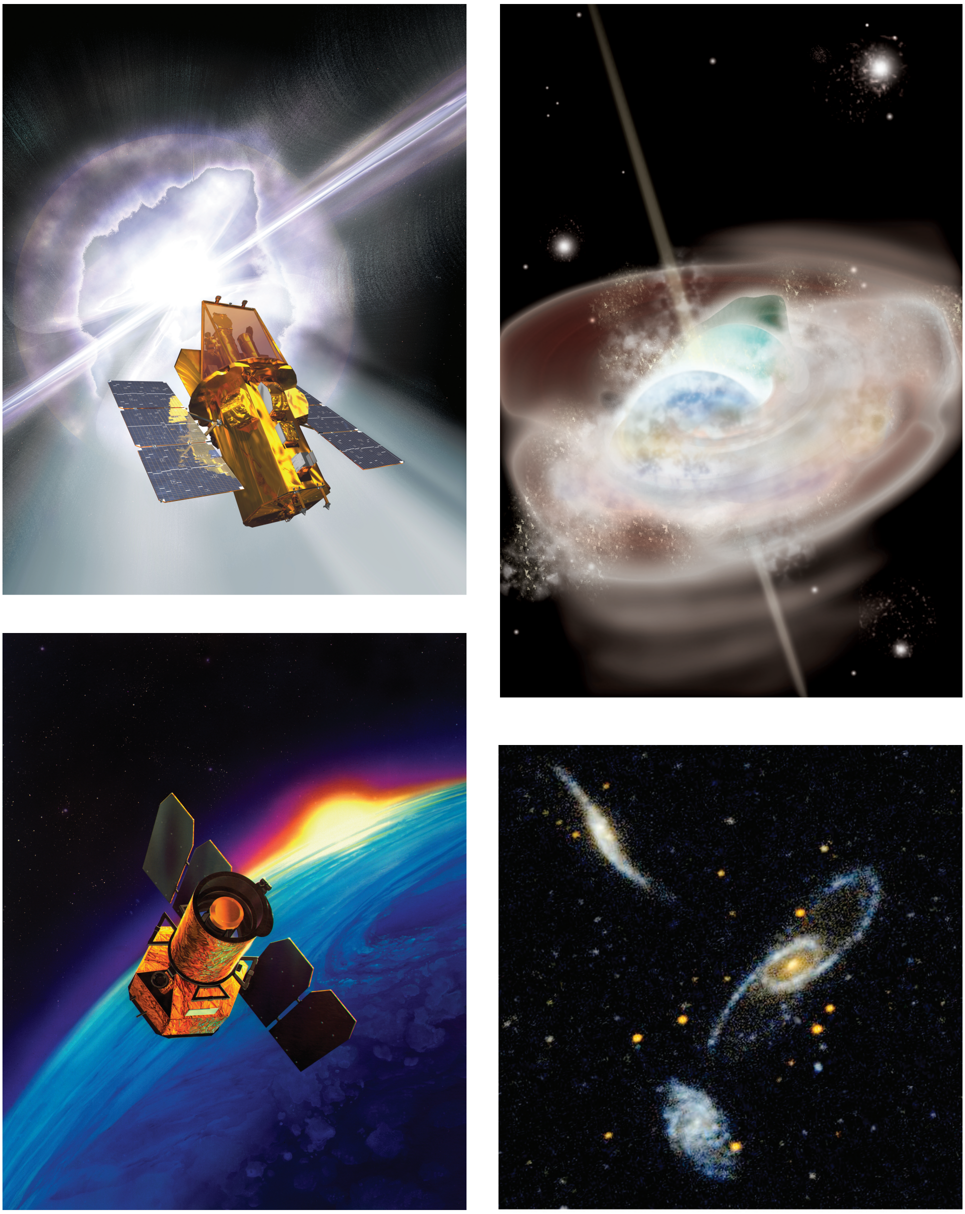

FIGURE 7.4 Continued.

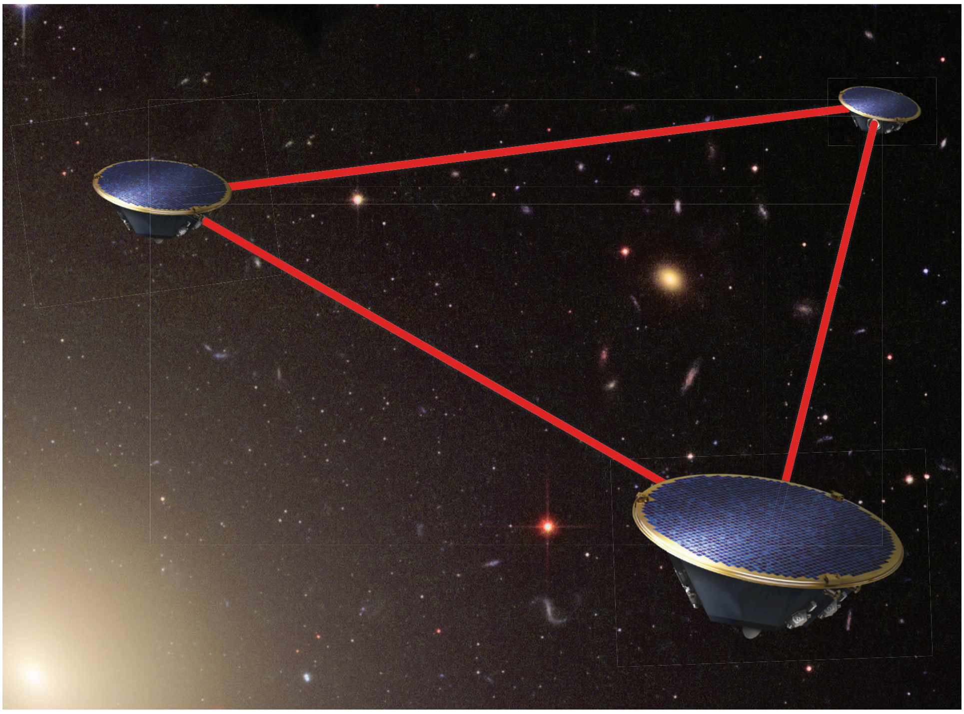

FIGURE 7.5 LISA comprises three spacecraft in an Earth-trailing orbit. It will be sensitive to waves with periods in the range of 10 seconds to 10 hours. The strain sensitivity is designed to be about 10^{-20} $Hz^{-1/2}$. The laser system is a 40-milliwatt Nd:YAG operating at a wavelength of 1 micron. SOURCE: NASA.

LISA has been studied for more than 20 years and was recommended by the 2001 decadal survey of astronomy and astrophysics and also by two other NRC reports.[16] It is a partnership between ESA and NASA that relies on the expertise of both agencies and scientific communities. The ESA portion of the mission is competing for the L-class slot of the Cosmic Vision program; the down-select process is beginning now (the other competitors in this class are IXO, see below, and the Europa Jupiter System Mission (EJSM), an outer-planets mission), with launch currently scheduled for the end of the decade. In the committee's independent cost and readiness analysis, the NASA 50 percent portion of the project cost is estimated to be $1.5 billion (at 70 percent confidence), with time to completion

[16] National Research Council, *Connecting Quarks with the Cosmos*, 2003, and *NASA's Beyond Einstein Program: An Architecture for Implementation*, 2007.

of about 9.5 years. The remaining technical risk was rated as medium if the currently identified main technical risks—involving micro-Newton thrusters, drag-free control, and a gravitational reference system—are all retired by a successful LISA Pathfinder mission, now scheduled for launch in 2012. The largest remaining technical challenge for the mission is identified as the successful deployment and operation of all three antennas.

In recommending LISA for continued development, the committee identified two key decision points. First, the LPF mission must be successful. Second, ESA must assign LISA it highest priority as an L-class mission. If either of these conditions is not satisfied, the committee recommends that a DSIAC be tasked to review the status of LISA mid-decade, in consultation with ESA, and to reconsider LISA's prioritization relative to other opportunities. Overall the recommendation and prioritization for LISA reflect its compelling science case and the relative level of technical readiness. Assuming a successful LISA Pathfinder, a 2016 new start should enable launch in the middle of the next decade.

Priority 4 (Large, Space). International X-ray Observatory (IXO)

IXO is a versatile large-area, high-spectral-resolution X-ray observatory (Figure 7.6). X-ray observations probe the hottest regions of the universe, where temperatures reach tens of millions Kelvin. Studying the hot component of the universe is central to understanding how galaxies and larger-scale structures form and how energy and matter cycle through galaxies and the circumgalactic medium, and to probing the observable matter closest to black holes and neutron stars. Hot gas

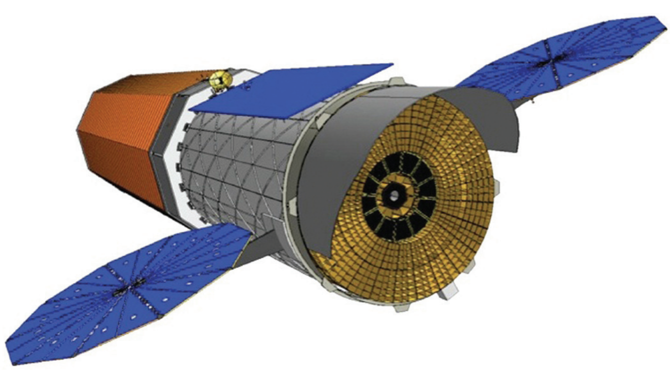

FIGURE 7.6 IXO contains a grazing incidence X-ray telescope with a 20-meter focal length and an effective area of around 3 square meters at 1 keV. The angular resolution from 0.3 to 7 keV is about 5 arcseconds, and a combination of dispersive and non-dispersive spectrometers provides excellent energy resolution over this energy range. SOURCE: NASA

constitutes the majority of ordinary matter in clusters of galaxies. Large-aperture, time-resolved, high-resolution X-ray spectroscopy is required for future progress on all of these fronts, and this is what IXO can deliver.

The IXO mission, a collaboration among NASA, ESA, and JAXA, will revolutionize X-ray astronomy with its large-aperture, energy-resolving imager. IXO is a relatively young mission concept that resulted from the merger of two long-standing proposals, ESA's XEUS mission and NASA's Constellation-X mission (which was recommended by AANM). At the heart of IXO is a 3-square-meter-aperture, lightweight focusing X-ray mirror with 5-arcsecond angular resolution. The key component of the IXO focal plane is an X-ray microcalorimeter spectrometer—a 40 × 40 array of transition-edge sensors covering several arcminutes of sky that measure X-ray energy with an accuracy of roughly 1 part per 1,000 (depending on energy). It will be launched to Lagrange point L2.

The independent cost and readiness analysis indicates a total appraised project cost of $5.0 billion (at 70 percent confidence), and the estimated time to completion is about 9.5 years. The survey's independent analysis concluded that the technical risk is medium high. Areas of particular concern include the challenge of successfully manufacturing the large-aperture mirror and achieving an angular resolution of 5 arcseconds. Uncertainties in total mass combined with a low-mass margin could require a larger, more expensive launch vehicle. In addition, several of the secondary instrument components are technologically immature (technology readiness level 3 or 4). Retiring this risk will require a substantial directed technology development program, estimated to cost about $200 million.

The path forward has two key decision points. The first relates to technical readiness. For IXO to be ready for a mission start, technology readiness must have progressed to the point that a down-select for the mirror technology can be made and cost uncertainties are reduced. The committee considers that in the current budget climate, allowing any major mission to exceed $2 billion in total cost to NASA would unacceptably imbalance NASA's astrophysics program. If the technology development program has not been successful in bringing cost estimates below this level, the committee recommends that descope options be considered to ensure that NASA costs remain below $2 billion.

The second decision point relates to ESA's choice for its next L-class mission slot. Since both IXO and LISA are close to 50-50 partnerships with ESA, the phasing of their development must be decided jointly. If LISA is selected for the first L-class launch slot, the investment in IXO this decade, although still substantial, can be limited to technology development sufficient to bring IXO to a technology readiness level of 5 or greater by 2020. This ordering would be consistent with the committee's priorities. However, if IXO is selected for the first L-class launch, NASA should request that a decadal survey implementation advisory committee review the IXO case and examine progress in the mission design and readiness. If the review is favorable, NASA should be prepared to invest immediately in technology development at a high level, and work with the project to define the partnership agreements.

On the basis of the above considerations, a budget of $4 million per year is recommended in the first several years of the decade to allow for risk reduction and mission definition, with an increase in the last half of the decade to a level of $20 million to $30 million per year, the minimum the committee estimates is necessary to develop critical technologies and prepare IXO to be mature and ready for consideration by the next decadal survey for a start soon thereafter. Descopes should be considered to ensure that the cost to NASA remains below $2 billion but reviewed to ensure that the baseline science requirements are still achieved. Investing 10 percent of NASA's eventual cost is consistent with the committee's other recommendations regarding mission-specific technology development. Prior to a start, NASA, in coordination with ESA and JAXA, should ensure that IXO's principal risks are retired, including a down-select of the critical mirror technology, with sufficient maturation to demonstrate the performance, mass, and cost.

The ranking of IXO as the fourth-priority large space mission reflects the technical, cost, and programmatic uncertainties associated with the project at the current time. However, many high-priority science questions require an X-ray observatory on this scale, continuing the great advances made by Chandra and XMM-Newton. Furthermore, the science of IXO is quite complementary to that of LISA. The committee therefore recommends that NASA begin by mid-decade an aggressive program to mature the mission and develop the technology so that this high-priority science mission can be realized.

Recommendations for New Space Activities—Medium Projects

Priority 1 (Medium, Space). New Worlds Technology Development Program for a 2020 Decade Mission to Image Habitable Rocky Planets

One of the fastest growing and most exciting fields in astrophysics is the study of planets beyond our solar system. The ultimate goal is to image rocky planets that lie in the habitable zone of nearby stars—at a distance from their star where water can exist in liquid form—and to characterize their atmospheres. Detecting signatures of biotic activity is within reach in the next 20 years if we lay the foundations this decade for a dedicated space mission in the next.

Achieving this ultimate goal requires two main necessary precursor activities. The first is to understand the demographics of other planetary systems, in particular to determine over a wide range of orbital distances what fraction of systems contain Earth-like planets. To this end, the committee recommends, as discussed earlier in this chapter, combined exploitation of the current Kepler mission, development and flight of the first-priority large mission WFIRST, and a vigorous ground-based research program. The second need is to characterize the level of zodiacal light present so as to determine, in a statistical sense if not for individual prime targets, at what level starlight scattered from dust will hamper planet detection. Nulling interferometers on NASA-supported ground-based telescopes (for example, Keck, and the Large Binocular Telescope) and/or on suborbital, SMEX, or MIDEX platforms could be used to constrain zodiacal light levels. A range of measurement techniques must be strongly supported to ensure that the detections extend to the relevant Earth-Sun distance range[17] for a sufficient sample of systems. After these essential measurements are made, the need for a dedicated target finder can be determined and the approach for a space-imaging mission will be clear. The programs above will enable the optimal technologies to be selected and developed.

For the direct-detection mission itself, candidate starlight suppression techniques (for example, interferometry, coronagraphy, or star shades) should be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade in preparation for a mission start early in the 2020 decade. The committee envisions that this program can be implemented at moderate funding levels early in this decade, but that it will require augmentation over current support levels for all of these activities. From the above considerations, a budget of $4 million per year is recommended in the first several years of the decade, in addition to the generally available technology development funds. If the scientific groundwork has been laid and the design requirements for an imaging mission have become clear by the second half of this decade, a technology down-select should be made. Furthermore, mission development should be supported at an appropriate level for the mission design and scope to be well understood. Initiating this activity will require significantly greater resource levels than the early-decade mission-enabling activities described above. It is currently difficult to anticipate the developments that could justify initiating this mission-specific development program, and the committee therefore recommends that a decadal survey implementation advisory committee be convened mid-decade to review progress both scientifically and technically to determine the way forward, and in particular whether an increased level of support associated with mission-specific technology development should commence. In this case a notional decadal budget of $100 million is proposed. However, the level of late-decade investment required is uncertain, and the appropriate level must be determined by a decadal survey implementation advisory

[17] The Spitzer Space Telescope was sensitive to dust located at wide separations from stars, analogous to the solar system's outer Kuiper belt, but not to analogs of the inner asteroid belt or the zodiacal dust close to Earth.

committee review. It could range between the notional budget used here up to a significant (perhaps on the order $200 million) mission-specific technology program starting mid-decade.

The committee's proposed program is designed to allow a habitable-exoplanet imaging mission to be well formulated in time for consideration by the 2020 decadal survey.

Priority 2 (Medium, Space). Technology Development for a 2020 Decade Mission to Probe the Epoch of Inflation

Detecting the B-mode polarization pattern on the cosmic microwave background impressed by gravitational waves produced during the first few moments of the universe both would provide strong evidence for the theory of inflation that is so crucial to our understanding of how structures form, and would open a new window on exotic physics in the early universe in regimes not accessible even to the most powerful particle accelerators on Earth. Progress in measuring both the polarization and the fine-scale anisotropy of the cosmic microwave background radiation is proceeding rapidly with ground-based telescopes in Antarctica and Chile and space-based instruments.

The recommended enhanced Suborbital program, as described below, as well as Missions of Opportunity made possible by an augmented Explorer program, will provide opportunities for substantive balloon experiments to probe the polarization signal to faint levels. NASA through the APRA program, as described below, should augment support for CMB technology development at a modest level. If the combined space and ground-based program is successful in making a positive detection of B-modes from the epoch of inflation, it is further recommended that NASA should then embark on an enhanced program of technology development, with a view to preparing a mature proposal for a dedicated space mission to study inflation through CMB observations for consideration by the 2020 decadal survey. If this observational goal is not met, then the suborbital programs and the broad technology development programs should continue to be supported at the same early-decade level with the goal of further improving detection limits.

In summary, significant progress on CMB studies, including the understanding of foregrounds, is certain given the successful operation of Planck and the suborbital and ground-based facilities that are currently operating or will come on line soon. A successful detection of B-modes from inflation could trigger a mid-decade shift in focus toward preparing to map them over the entire sky. In this case a notional decadal budget of $60 million is proposed. However, the level of late-decade investment required is uncertain, and the appropriate level should be studied by a decadal survey implementation advisory committee review. It could range between the notional budget used here up to a significant (perhaps on the order of $200 million) mission-specific technology program starting mid-decade.[18]

Recommendations for New Space Activities—Small Projects

Most small missions and contributions to non-NASA programs can be competed within the Explorer program and are best handled there through the peer-review process. However, one time-critical opportunity with compelling scientific return—the Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission—exceeds the scale allowed by Explorer MoOs, and the committee recommends that NASA proceed with contributions to its development as described below. The committee considered it along with the competed investigator programs that are also described below, and does not rank any of these small-scale opportunities.

U.S. Contribution to the JAXA-ESA SPICA Mission

The tremendous success of the Spitzer Space Telescope has spurred the development of a yet-more-powerful mid- and far-infrared mission, the Japanese-led SPICA mission. It addresses many of this report's identified science goals, especially understanding the birth of galaxies, stars, and planets as well as the cycling of matter through our own interstellar medium and dusty gas in nearby galaxies. SPICA will have a cooled 3.5-meter aperture and operate at wavelengths from 5 to 210 microns. The planned launch date is 2018.

The committee recommends that the United States should join this project by contributing infrared instrumentation, which would exploit unique U.S. expertise and detector experience. The committee received a proposal from a project called BLISS which provided one possible way to meet this opportunity and was rated highly by the survey's Program Prioritization Panel on Electromagnetiic Observations from Space. NASA has recently issued a call for proposals for science investigation concept studies that will elicit more ideas. Such participation would provide cost-effective access to an advanced facility for the U.S. research community and full participation in the science teams. Because JAXA and ESA are currently moving ahead, joining SPICA is time-sensitive, and so the committee urges NASA to work with JAXA to determine the optimal phasing of an Announcement of Opportunity for contributions. A notional budget of $150 million, including operations over the decade, is recommended.

[18] For budget planning purposes the committee set aside $150 million to account for the most likely scenario if this program or the New Worlds program goes forward at a high funding level.

Small Additions and Augmentations to NASA's Core Research Programs

As discussed in Chapter 5, NASA's core research programs—such as support for individual investigator grants, data management, theoretical studies, and innovative technology development—are fundamental to mission development and essential for scientific progress. They provide the foundation for new ideas that stretch the imagination, and they lay the groundwork for nearer-term Explorer programs as well as far-future vision missions. They provide the means to interpret the results from currently operating missions. Maintaining these core activities, even in the face of cost overruns from major missions, has high priority and is the most effective way to maintain balance in the research program.[19]

To support the new scientific opportunities of the coming decade, and to lay the foundations for future missions for 2020 and beyond, the committee recommends several augmentations to core activities, as well as some new programs of small scale. These are unranked and listed in alphabetical order. Programs that are not mentioned are assumed to proceed with existing budget profiles, subject to senior review recommendations, although the committee emphasizes the importance of many small elements of the core research programs described in Chapter 5.

Astrophysics Theory Program

New investments in the Astrophysics Theory Program (ATP) will be amply repaid in the form of new mission concepts and enhanced scientific return from existing missions. A $35 million augmentation or 25 percent is recommended.

Definition of a Future Ultraviolet-Optical Space Capability

Following the fourth servicing mission, the Hubble Space Telescope (HST) is now more capable than ever before and is enabling spectacular science, including observation at ultraviolet wavelengths. No more servicing missions are planned, and NASA intends to deorbit HST robotically at the end of the decade. The committee endorses this decision. Meanwhile, the results from FUSE, GALEX, and the HST's Cosmic Origins Spectrograph now show that as much could be learned about the universe at ultraviolet wavelengths as motivated the proposal and development of JWST for observations at infrared wavelengths. Topics that are central

[19] See for example the following National Research Council reports: *An Enabling Foundation for NASA's Earth and Space Science Missions* (2009), *A Performance Assessment of NASA's Astrophysics Program* (2007), *An Assessment of Balance in NASA's Science Programs* (2006), *Review of the Science Mission Directorate's Draft Science Plan: Letter Report* (2006), and *Supporting Research and Data Analysis in NASA's Science Programs: Engines for Innovation and Synthesis* (1998), all published by The National Academies Press, Washington, D.C.

to the survey's committee's proposed science program include understanding the history of the intergalactic medium and its cycling in and out of galaxies as well as the evolution of normal stars and galaxies.

Key advances could be made with a telescope with a 4-meter-diameter aperture with large field of view and fitted with high-efficiency UV and optical cameras/spectrographs operating at shorter wavelengths than HST. This is a compelling vision that requires further technology development. The committee highly recommends a modest program of technology development to begin mission trade-off studies, in particular those contrasting coronagraph and star-shade approaches, and to invest in essential technologies such as detectors, coatings, and optics, to prepare for a mission to be considered by the 2020 decadal survey. A notional budget of $40 million for the decade is recommended.

Intermediate Technology Development

As described in Chapter 5, a technology development gap has emerged between "Blue Skies" investigations and mission-specific development. The gap is formally associated with NASA's technology readiness levels 3 through 5. Research and analysis (R&A) funding in this program has fallen in recent years. The committee recommends that funding for such medium-term technology development be augmented at the level of $2 million per year starting early in the decade, ramping up to an augmentation of $15 million per year by 2021.

Laboratory Astrophysics

As described in Chapter 5, support and infrastructure for laboratory astrophysics are eroding both in the National Laboratories and in universities. Yet the current Herschel mission, the next decade's JWST and ALMA, and the future IXO will provide unprecedented spectroscopic sensitivity and resolution, enabling new quantitative diagnostics of the interstellar medium, star-forming regions, and hot plasmas in a wide variety of astrophysical contexts. With these improvements in spectroscopic capabilities in the submillimeter, infrared, and X-ray regions, extracting quantitative information will in many cases become limited by available knowledge of atomic and molecular transition data and cross sections. Further, detailed understanding of magnetized plasmas, the formation of molecules, and complex chemical reactions at a level that can only be obtained experimentally is of central importance to interpreting data from these missions.

It is recommended that NASA, in coordination with DOE, assess the level of funding available for laboratory astrophysics through the APRA program relative to the requirements of its current and future spectroscopic missions. Funding through APRA that is aimed at mission-enabling laboratory astrophysics should be augmented at a level recommended by this scientific assessment. While the costs of obtaining the data that will be needed in the coming decade are difficult to estimate, an increase of 25 percent over the current budget, or a notional budget increment of $20 million over the decade, may be required.

Suborbital Program

NASA-supported balloon and rocket experiments, known collectively as the Suborbital program, enable science, develop technology, and provide an invaluable training ground (Figure 7.7). Many highly successful Explorer missions, such as GALEX and WMAP, were preceded by balloon-borne observations and technology demonstrations.

FIGURE 7.7 Launch of the balloon-borne instrument ARCADE (Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission) in 2009. SOURCE: NASA/GSFC/JPL/UCSB.

Recent efforts by NASA management have halted the long erosion of the core Suborbital and R&A programs, out of which balloon and rocket payload development is funded.[20] However, additional resources are needed to support the high-priority science areas identified by this survey. NASA should investigate and, if practical and affordable, implement the orbital sounding rocket capability described by NASA's Astrophysics Sounding Rocket Assessment Team, which would provide a few thousand times more observing time than normal sounding rocket flights, greatly increasing the science that can be accomplished from rockets. The priority in the balloon program should be to increase the launch rate and develop new payloads. The ultralong-duration balloon (ULDB) program is attractive, because it provides about a factor-of-three more observing time than Antarctic long-duration balloons (LDBs) as well as mid-latitude long-duration flights, but it is expensive. One of this survey's priority science areas, the CMB, along with related dark matter and cosmic-ray detection experiments, has primary requirements for frequent access and increased total observing. If it is more cost-effective per observing day to expand the LDB program and improve its facilities and recovery reliability, then this should have the highest priority.

To increase the launch rate by about 25 percent, it is recommended that the R&A program be augmented by $5 million per year to accommodate the selection of additional balloon and rocket payloads. In addition, $10 million per year will be needed to support the additional launches and improvements in infrastructure.

Theory and Computation Networks

As described in Chapter 5, as observational capabilities advance, the theoretical efforts required to anticipate, understand, and interpret data become more complex. The scientific programs recommended by Astro2010 in many cases require large coordinated theory and computational efforts. These are of a scale inconsistent with the funding levels of the individual investigator grants currently supported by NASA's Astrophysics Theory Program. Examples of particular urgency include cosmological simulations of large-scale structure formation, modeling of galactic flows and feedback, and the general relativistic simulations of physical processes associated with the mergers of neutron stars.

A NASA annual funding level of $5 million, capable of supporting about eight networks, is recommended. The level of funding should be driven by the quality and relevance to NASA's missions of proposals received in response to competitive peer review. The networks should be funded in addition to maintaining a healthy Astrophysics Theory Program, not at its expense.

[20] For further information see the 2009 National Research Council report *An Enabling Foundation for NASA's Earth and Space Science Missions.*

Recommendations for New Ground-Based Activities—Large Projects

Priority 1 (Large, Ground). Large Synoptic Survey Telescope (LSST)

The Large Synoptic Survey Telescope (LSST) would employ the most ambitious optical sky survey approach yet and would revolutionize investigations of transient phenomena. It would address the pressing and fundamental question of why the expansion rate of the universe is accelerating, and would tackle a broad range of priority science questions ranging from understanding the structure of our galaxy to elucidating the physics of stars. LSST (Figure 7.8) opens a new window on the time-variable universe and therefore promises discoveries yet to be imagined. LSST's observations repeatedly cover large areas of sky following a preordained and optimized sequence to create a data set that addresses a majority of SFP-identified questions.

LSST's dark energy program centers on using weak gravitational lensing to constrain the rate of growth of large-scale structure, as well as detecting supernova explosions. For these studies LSST's data are an essential complement to the near-infrared measurements performed by WFIRST from space. LSST's data set would permit both real-time investigations for studying variable objects and a vast archive that will be mined far into the future. In time-domain studies, LSST's specific goals include mapping of near-Earth objects (as mandated by Congress), supernovae, gamma-ray bursts, variable stars, and high-energy transients. Its archival science will include mapping the Milky Way and the distant universe, creating an accurate photometric and astrometric data set, studying stellar kinematics, and performing a census of the solar neighborhood. It is also seen as a prime discovery engine.

LSST is proposed as an 8.4-meter telescope to be sited in Chile. It is specially designed to produce excellent images over a very wide 3.5-degree field of view. It will image the sky repeatedly in six colors in the visible band (0.3 to 1.0 micrometer). Over its lifetime of 10 years, it will observe each region of the sky 1,000 separate times. The 1,000 separate images will be used to make a "cosmic movie" to search for objects that move or whose brightness varies. By adding these images, it will also produce a very deep map of roughly half of the entire sky. LSST will produce a calibrated data set and analysis tools for the astronomy and astrophysics community. It will also facilitate the creation, by researchers outside the project, of additional science products that may be incorporated into the LSST data system. The data will be open access with no proprietary period for U.S. and Chilean astronomers; other non-U.S. partners that join will be expected to contribute to the cost of operations. LSST was conceived as a joint NSF-DOE project, with the latter taking responsibility for the camera. It has benefited from private donations and has acquired international partners. The combined primary-tertiary mirror has been cast and the grinding has begun.

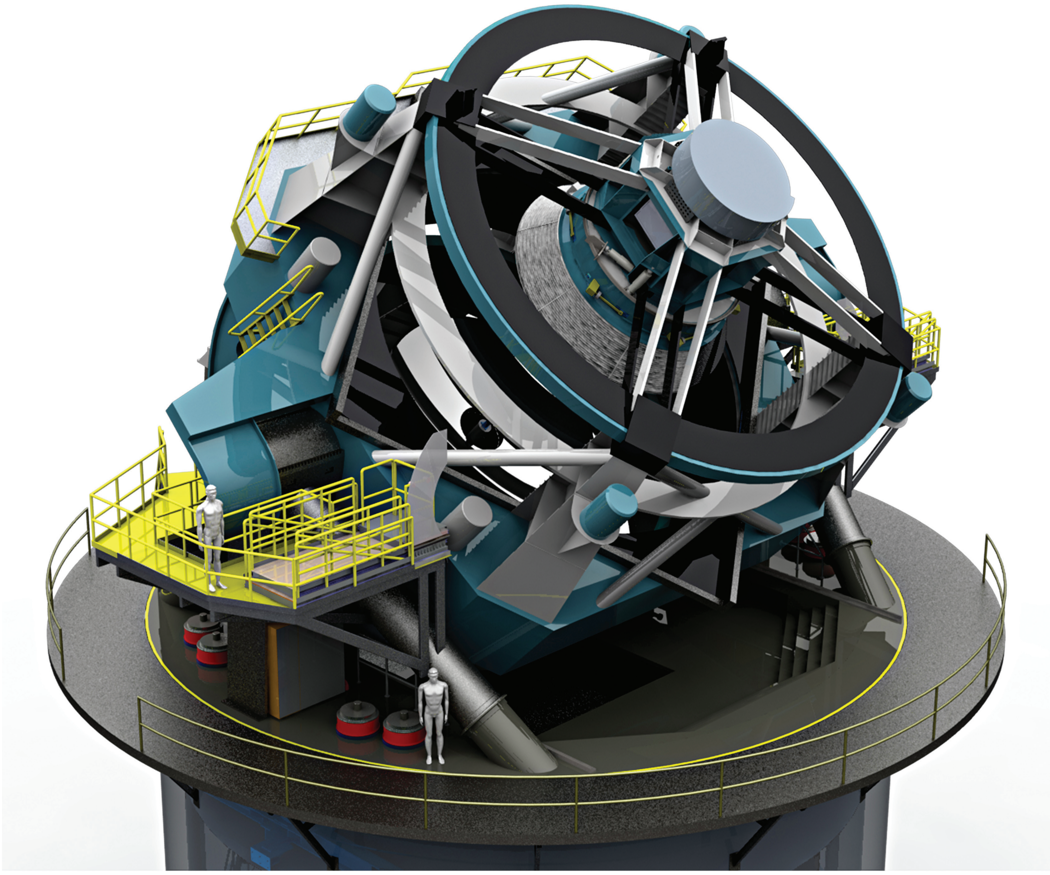

FIGURE 7.8 LSST has a three-mirror design with the primary and tertiary mirror combined and cast from a single blank. Preliminary grinding is already underway, and the secondary mirror has also been cast. An important figure of merit for a survey telescope is the etendue, which is the product of the field of view and the area. This is 320 m^2 $degree^2$ for LSST. The 3 GPx camera will read out in less than 2 seconds every 15 seconds, and more than 100 petabytes of data will be accumulated over the 10-year project lifetime. The limiting magnitude in a single visit is r = 24.5. The camera pixel scale is roughly 0.2 arcsecond, and the median seeing at the site is roughly 0.67 arcsecond. SOURCE: LSST Corporation.

The technical risk of LSST as determined by the survey's cost appraisal and technical evaluation (CATE) process was rated as medium low. The committee did identify additional risk with establishing data management and archiving software environments adequate to achieving the science goals and engaging the astronomical community. The appraised construction cost is $465 million with a time to completion of 112 months. The committee recommends that LSST be started as soon as possible, with, as proposed by the project, two-thirds of the construction costs borne by NSF through its MREFC line and a quarter by DOE using Major Item of Equipment (MIE) funds. The estimated operations cost is $42 million per year over its 10-year lifetime, of which roughly $28 million is proposed to be borne by the U.S. agencies—the committee recommends two-thirds of the federal share of operations costs be borne by NSF and one-third by DOE. It is recommended that any extended mission should only happen following a successful senior review. By its very nature LSST will stimulate a large number of follow-up studies, especially of a spectroscopic character. The planning and administration of an optimized plan for follow-up studies within the public-private optical-infrared system could be carried out by the National Optical Astronomy Observatory.

The top rank of LSST is a result of its capacity to address so many of the identified science goals and its advanced state of technical readiness.

Priority 2 (Large, Ground). Mid-Scale Innovations Program

Science and technology are evolving rapidly. Each decade, new discoveries open new opportunities, and scientists and engineers find novel and innovative approaches to designing instruments. Although there are regularly competed opportunities on timescales shorter than a decade for moderate-scale missions in space, on the ground there is no program that can compete and select mid-scale projects based on scientific merit and technical readiness as instruments mature and science advances. The committee was impressed by the large number of white-paper submissions for mid-scale ground-based projects that offer compelling science and novel technical approaches but that cannot be evaluated without a proper scientific and technical peer review.

The committee recommends, as its second-highest priority, a competed program, based on NASA's highly successful Explorer model, that would enable moderate-scale projects to be frequently selected through peer review. Like the Explorer program, a mid-scale instrumentation and facility program at NSF—a program that the committee calls the Mid-Scale Innovations Program—would provide first-class science at moderate cost and would address the need to involve and train students in experiment design and instrumentation.

The need for such a program is driven by the fact that NSF-AST does not have a formal mechanism for competing proposals in the price range between the Major Research Instrumentation (MRI) program (less than $4 million) and the MREFC line (greater than $135 million in FY2010). It does accept unsolicited proposals in the mid-scale category, several of which have been funded, but without the head-to-head competitive peer review that ensures that the highest-priority needs are met. The committee therefore recommends the establishment of a competed Mid-Scale

Innovations Program for instrumentation and facilities in order to capitalize on a large variety of exciting science opportunities over the upcoming decade.

The program should issue roughly annual calls for proposals in two categories: (1) conceptual and preliminary design activities and (2) detailed design and construction projects. Important elements of the program include standard peer review and selection criteria with special attention to scientific merit, relevance to community-established strategic goals and roadmaps, project management, and planning for both operations and data archiving funding. Operations and data archiving could be proposed, but not necessarily fully funded, by the program. A periodic review of ongoing projects with clearly stated procedures for funding continuation or termination is recommended. Co-funding of mid-scale projects from non-NSF sources would be allowed but not required. The Mid-Scale Innovations Program funding line should be established at a level that enables the selection of a minimum of seven such projects spanning a range of scales over the decade—a rate that provides regular opportunities and accomplishes a broad range of science.

Of the 29 proposals for ground-based mid-scale projects submitted as white papers to the survey, a subset was considered compelling by the committee. Although it is not appropriate for the committee to rank concepts for a competed line, it lists in Table 7.1 the activities it found compelling. The indicated cost categories are based on submitted descriptions and not on any independent committee review. Appendix D provides additional background information on these projects. Other examples may be found in the PPP reports. Many similar instrument and small-facility concepts will undoubtedly emerge over the decade. It is important that the Mid-Scale Innovations Program maintain a balance between large and small projects. Indeed, such a program in NSF-AST could take on some of the larger Advanced Technologies and Instrumentation (ATI) projects, so that ATI would emphasize advanced technology development together with instrumentation below ~$2 million.

The recommended Mid-Scale Innovations Program is aimed primarily at instrumentation and facilities in order to be consistent with the goals of the program at NSF's Directorate for Mathematical and Physical Sciences (NSF-MPS) and with the recommendations of the National Science Board (NSB)[21] and NRC reports, but proposals for other types of initiatives in this cost range could be considered for funding if they present an especially compelling scientific case.

To support the committee's recommendation, almost $400 million would be needed in this line over the decade, in addition to the funds needed to complete

[21] National Science Board, *Science and Engineering Infrastructure for the 21st Century*, National Science Foundation, Arlington, Va., 2002; National Research Council, *Advanced Research Instrumentation and Facilities*, The National Academies Press, Washington, D.C., 2006.

TABLE 7.1 Projects Thought Compelling for the Mid-Scale Innovations Program (in alphabetical order)

Project Name	Science Goal	Cost Range[a]
Big Baryon Oscillation Spectroscopic Survey	Determine the cause of the acceleration of the universe.	Upper
Cosmic Microwave Background Measurements	Detect the signature of inflation and probe exotic physics in the earliest moments of the universe.	Middle
Exoplanet Initiatives	Develop radial velocity surveys and spectrometers to determine the properties of extrasolar planets; understand extrazodiacal light levels.	Middle and Lower
Frequency Agile Solar Radiotelescope	Understand the Sun's atmosphere.	Upper
High-Altitude Water Čerenkov Experiment	Map the high-energy (>1 TeV) gamma-ray sky.	Lower
Hydrogen Epoch of Reionization Array	Determine how the universe is ionized after the formation of the first stars.	Upper
Next Generation Adaptive Optics Systems	Enable near-infrared and visible wavelength imaging and spectroscopy at spatial resolution better than that of HST to address a broad science program from exoplanet studies to galaxy formation.	Middle and Upper
North American Nanohertz Observatory for Gravitational Waves	Detect gravitational waves from the early universe through pulsar timing.	Upper

[a] Upper: $40 million to $100 million, middle: $12 million to $40 million, lower: <$12 million where costs are total project costs.

similar projects already started. The committee recommends funding of this program at a level that builds up to $40 million per year by mid-decade (additional funds over the decade would fall between $93 million and $200 million). The current level of funding for mid-scale projects in NSF-AST, which occurs on an ad hoc basis, is estimated at roughly $18 million per year, including some technology, design, and development work for LSST, GSMT, and SKA.

The principal rationale for the committee's ranking of the Mid-Scale Innovations Program is the compelling number of highly promising projects with costs between the MRI and MREFC boundaries, plus the diversity and timeliness of the science that they could achieve. There are advantages to putting this program at the NSF-MPS level where it would serve all the divisions, and also those to putting it at the NSF-AST level.

Priority 3 (Large, Ground). Participation in a Giant Segmented Mirror Telescope (GSMT)

Large telescopes in the 8- to 10-meter class have revolutionized the world of optical and near-infrared astronomy. Newly developed adaptive optics systems, which remove image distortions caused by the atmosphere, have made them even more powerful. Astronomers are poised to take the next major step—adaptive optics telescopes with 3 times the diameter, 10 times the optical collecting area, and up to 80 times the near-infrared sensitivity compared to existing telescopes. These Giant Segmented Mirror Telescopes (GSMTs) will be essential to understanding the distant galaxies discovered by JWST and to obtaining spectra of the faint transients found by LSST, and they will be transformative for a broad range of science aimed at understanding targets ranging from stars and exoplanets to black holes. Although they will function as observatories, they are integral parts of each of the survey's target science areas as explained in Chapters 1 and 2. Operating in the optical and infrared (at 0.3 to 2.5 microns), the GSMTs excel at high-spectral- and high-spatial-resolution spectroscopy and will have a relationship to JWST similar to that of the 8- to 10-meter-class telescopes to HST.[22]

With every enormous leap in sensitivity come new discoveries we cannot anticipate, but the broad impact the GSMTs will have on the survey's identified science questions is clear. The very first galaxies in the universe that will be found by JWST will require GSMTs for follow-up so as to determine their internal dynamical properties by studying the bulk motions of stars in a way that complements the gas observations of ALMA. GSMTs would also monitor how the chemical elements are built up. Their superb spatial resolution and astrometric capabilities would enable them to follow the orbits of individual stars around the several-million-solar-mass black hole in the center of our Milky Way galaxy so as to obtain precision measurements of fundamental galactic parameters. Direct imaging of exoplanet systems using the advanced adaptive optics cameras on these telescopes would also be an exciting area of study, given that GSMTs will have the highest angular resolution in the visible through infrared of any existing or planned facility, ground or space. They would also be able to study the reflected infrared emission of planets in the habitable zone. The ability of a GSMT to perform direct spectroscopy on very faint galaxies would be crucial in efforts to elucidate the properties of dark matter and merging black holes. These telescopes would transform understanding of stellar astronomy by taking high-dispersion spectra of local stars, mapping the flow of gas into and out of massive galaxies during their formative stage, and studying the formation of protoplanetary systems.

[22] Specifically, HST discovered many new classes of objects, and the larger ground-based telescopes with their superior spectroscopic capabilities were needed to determine where and what they are.

As discussed in Chapter 3, there are three projects underway in the world to construct and operate a new generation of extremely large telescopes with diameters in the range of 23 to 42 meters (Figure 7.9). The Giant Magellan Telescope (GMT) is composed of seven 8.4-meter mirrors and has an aperture equivalent to a single 23-meter mirror; it will be sited at the Las Campanas Observatory (Chile). The GMT design builds on the success of the two 6.5-meter Magellan Telescopes. The Thirty-Meter Telescope (TMT) is composed of almost 500 1.44-meter segments, has an aperture equivalent to a single mirror 30 meters in diameter, and will be sited at Mauna Kea (Hawaii). It builds on the success of the two 10-meter Keck Telescopes. The European Extremely Large Telescope (E-ELT) has a segmented mirror design with an aperture equivalent to a single mirror 42 meters in diameter. Its recommended site is at Cerro Armazones in Chile. The project is led by the European Southern Observatory (ESO) and has a mirror segment design similar to that of TMT.

The committee concluded that more than one GSMT will be required in the world to fully exploit the identified science opportunities. The reasons are that there are advantages to having capability in two hemispheres, or two in the same hemisphere with different instrument capabilities requiring different optimizations of telescope design, and that so many new scientific problems can be addressed that any credible number of GSMTs is likely to be oversubscribed. It is imperative that at least one of the U.S.-led telescope projects have U.S. federal investment. Such a federal role will leverage the very significant U.S. private investment, will maximize the potential for the project's success, will help to optimize the U.S. scientific return on other federal investments (ALMA, JWST, and LSST), and will position the NSF for leadership in future large-telescope projects beyond GSMT. Since both GMT and TMT are already international public-private partnerships, federal involvement with either one is consistent with the international collaboration strategy that is a recurring theme in this survey and would ensure U.S. leadership in one international large telescope. Such leadership would further another important strategy advocated in this report: cooperation with other countries so as to develop complementary capabilities that will maximize the science output. In the case of GSMT this means coordination with ESO on technology development and instrument selection to create a global system of GSMTs with optimal complementary and scientific reach. The committee notes that public time on a GSMT would, in principle, be subject to the open skies policy in effect for all federally supported U.S. telescopes. It is the committee's hope that a result would be corresponding reciprocal access to major optical-infrared telescopes abroad.

The committee reviewed a technical risk assessment and sensitivity analysis of the anticipated cost and schedule for GMT and TMT that indicated the risk is medium to medium high. A cost sensitivity study based only on the telescope optics and instruments concluded that the construction costs of GMT and TMT would be \$1.1 billion and \$1.4 billion, respectively (at a 70 percent confidence

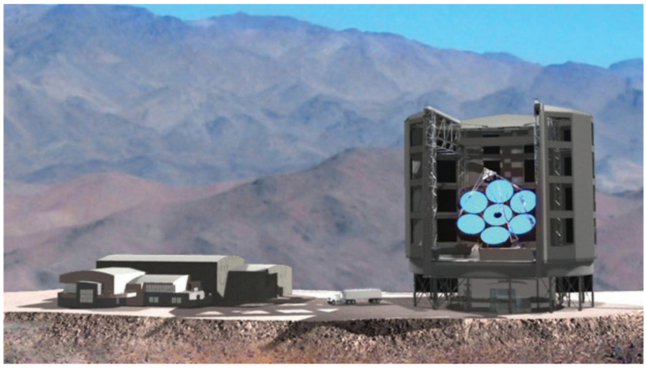

FIGURE 7.9 The two U.S. Giant Segmented Mirror Telescope projects. *Upper:* The Giant Magellan Telescope is a 25-meter-class telescope comprising seven 8.4-meter subapertures, one of which is already undergoing polishing. Laser tomography will provide adaptive optics correction in small fields over much of the sky, and correction for ground-level seeing will be incorporated over large fields. The baseline project includes an initial suite of three to four instruments to be selected in 2011 from eight concepts currently in development. Artist's rendering of GMT and support facilities at Las Campanas, Chile. SOURCE: Courtesy of GMTO; image by Todd Mason/Mason Productions. *Lower:* The Thirty Meter Telescope primary mirror comprises 492 hexagonal segments with active control and a 30-meter-effective-diameter aperture. An on-axis segment has been cast and polished, and an off-axis segment is currently undergoing polishing. Nine instruments are planned for the first decade of operations, of which three are planned for first light. Most of these instruments operate in conjunction with sophisticated adaptive optics systems. SOURCE: TMT Observatory Corporation.

level). Assuming the current status of the projects, the dates for full operations of the two telescopes (defined as including three instruments and the adaptive optics system) were estimated as spring 2024 for GMT, and between summer 2025 and summer 2030 for TMT depending on assumptions about segment manufacture and delivery. The telescope projects estimated their annual operations costs (including facility and instrument upgrades) as being $36 million for GMT and $55 million for TMT. Although the committee did not analyze these estimates in detail, they are far below the usual rule of thumb for large projects (10 percent of construction costs per year); should the projects go forward, their operations costs will need to be scrutinized in considerable detail. The committee did not evaluate the cost estimate or risks for the E-ELT, but the ESO estimate is €1 billion with a start of operations in 2018.

The two U.S.-led projects, GMT and TMT, are in fairly advanced states of design. GMT has already cast one of its six off-axis mirrors, which is currently being polished. TMT has cast, polished, and mounted an on-axis segment and is in the process of polishing an off-axis segment. Furthermore, through a combination of private and international partnerships, both projects have made considerable progress on their financing. The question, now, is whether or not the federal government can afford to become a partner in one of these projects and, if so, which one. The arguments for federal partnership are strong. First, the science case for a GSMT is highly compelling, and a federal share will ensure access to observing time for all U.S. astronomers, not just those associated with partner institutions.[23] This is a principle that is similar to the Telescope System Instrumentation Program (TSIP) program philosophy that has been so successfully implemented with respect to existing privately operated telescopes. Second, partnership can greatly enhance and improve these projects by bringing a much larger experience base and resources to them. This will be particularly important during the operations phase when funds to run the telescopes must be found and new and expensive instruments will need to be constructed.

In the committee's judgment, due to the severe budget limitations, a federal partnership in a GSMT will be limited to a minority role with one project. For the construction phase, a potential MREFC funding wedge opens up in the second half of the decade (after ALMA, ATST, and LSST have passed their peak funding) that would allow for a federal share in a GSMT to be supported by the MREFC line by the end of this decade. For the operations phase, in the optimistic budget-

[23] Institutional members as of May 2010 were, for GMT, Astronomy Australia Limited, the Australian National Observatory, Carnegie Institution for Science, Harvard University, Korea Astronomy and Space Science Institute, Smithsonian Astrophysical Observatory, Texas A&M University, the University of Texas at Austin, and the University of Arizona, and for TMT were the Association of Canadian Universities for Research in Astronomy, California Institute of Technology, and the University of California.

doubling funding scenario, some funding could be available by the last few years of the decade; in the flat budget scenario, few if any operations funds would be available in this decade.

However, the GSMT projects are at a pivotal point where some form of commitment from the U.S. government at this time will encourage additional collaboration and is crucial to having the projects go forward at all. Owing to the highly compelling science case for this class of telescope, the committee recommends immediate selection by NSF of one of the two U.S.-led GSMT projects for a future federal investment that will secure a significant public partnership role in the development, the operation, and telescope access. This action should facilitate access to and optimize the benefit of the largest ground-based telescopes for the entire U.S. community, by leveraging the significant private and international investments in this frontier endeavor. The committee further recommends as a goal that access should be sought at the level of at least a 25 percent share. This share could be secured through whatever combination of construction (that is, MREFC), operating funds, and instrumentation support is most favorable.

The committee believes that access to a GSMT will, as opportunities opened by large telescopes have in the past, transform U.S. astronomy by means of its broad and powerful scientific reach, and that federal investment in a GSMT is vital for the United States to be competitive in ground-based optical astronomy over the next two decades. These are the main reasons for its strong recommendation by the survey. The third-place ranking reflects the committee's charge, which required the prioritization to be informed not only by scientific potential but also by the technical readiness of the components and the system, the sources of risk, and the appraisal of the costs. LSST and several of the concatenation of candidates for the Mid-Scale Innovations Program were deemed to be ahead of GSMT in these areas.

Priority 4 (Large, Ground). Participation in an Atmospheric Čerenkov Telescope Array (ACTA)

The last decade has seen the coming of age of very high energy (TeV) astronomy. Very high energy gamma-ray photons are observed from cosmic sources through the flashes of Čerenkov light that they create in Earth's atmosphere. These events can be observed by large telescopes on the ground on moonless and cloudless nights, and the directions and the energies of individual photons measured. After a long U.S.-led period of development of this technique which yielded the discovery of a handful of sources, the field has taken off. The European facilities, HESS in Namibia and MAGIC in the Canary Islands, together, now, with the U.S. facility VERITAS in Arizona, have discovered 100 sources. These include active galactic nuclei, pulsars, supernova remnants, and binary stars. Astrophysicists have learned much about particle acceleration and can now rule out some models of fundamental physics as well as constrain the properties of putative dark matter particles. Further progress is now dependent on building a larger facility exploiting new detector technology and a larger field of view so that the known sources can be studied in more detail and the number of sources can be increased by an order of magnitude (Figure 7.10).

Both the U.S. and the European communities are developing concepts for a next-generation array of ground-based telescopes with an effective area of roughly 1 square kilometer. The U.S. version of this facility (AGIS, the Advanced Gamma-ray Imaging System) was evaluated by the survey and the total cost, estimated to exceed $400 million, was considered too expensive to be entertained, despite technical risk being medium low. The European Čerenkov Telescope Array (CTA) is in a more advanced stage, and there is advantage in sharing the costs and operations in a Europe-U.S. collaboration. The committee recommends that the U.S. AGIS project join CTA for collaboration on a proposal that will combine the best features of both existing projects. Funding availability is likely to permit U.S. participation only as a minor partner, but the promise of this field is so high that continued involvement is strongly recommended. U.S. funding should be shared among DOE, NSF-AST, and NSF-PHY, as happened with VERITAS, and a notional $100 million spread between the agencies over the decade is recommended. Given the large project cost uncertainties, the current lack of a unified project plan, the project ranking, and the likely budget constraints in the coming decade, it will be necessary for the agencies to work quickly with the AGIS/CTA group to define a scope of U.S. involvement that is both significant and realistic.

FIGURE 7.10 ACTA would be, like the pictured VERITAS (Very Energetic Radiation Imaging Telescope Array System), an array of Čerenkov telescopes used to detect very high energy (TeV) gamma rays emanating from astrophysical sources. The proposed ACTA telescope would be a larger-scale international version of this facility and similar ones located in Namibia and the Canary Islands that would increase the sensitivity by roughly an order of magnitude. SOURCE: Image courtesy of Steve Criswell, SAO.

The recommendation for ongoing U.S. involvement in TeV astronomy is based largely on the demonstrated recent accomplishments of this field and the prospect of building fairly quickly a much more capable facility to address a broad range of astronomy and physics questions over the next decade.

Recommendation for New Ground-Based Activities—Medium Project

Only one medium project is called out, because it is ranked most highly. Other projects in this category should be submitted to the Mid-Scale Innovations Program for competitive review.

Priority 1 (Medium, Ground). CCAT

CCAT (formerly the Cornell-Caltech Atacama Telescope) would be a 25-meter telescope operating in survey mode over wavelengths from 200 microns to 2 millimeters (Figure 7.11). CCAT is enabled by recent, dramatic advances in the ability to build millimeter-wave cameras with more than an order of magnitude more spatial elements than previously possible. This technical advance will enable a powerful submillimeter and millimeter telescope that can perform sensitive imaging surveys of large fields. ALMA, operating over the same band, is scheduled to begin full operations in 2014 and will produce high-resolution images and spectra of faint, and in some cases distant, sources. However, ALMA has a small field of view and is therefore inefficiently used to find the sources that it studies. CCAT will therefore be an essential complement to ALMA. It would excel as a sensitive survey facility, both for imaging and multiobject spectroscopy, with a field of view 200 times larger than that of ALMA. With a broad scientific agenda, CCAT will enable studies of the evolution of galaxies across cosmic time, the formation of clusters of galaxies, the formation of stars in the Milky Way, the formation and evolution of planets, and the nature of objects in the outer solar system.

The committee estimates a total development and construction cost of $140 million and an estimated start of operations in 2020.[24] The technical risk was assessed as medium. It is recommended that NSF plan to fund $37 million of the construction cost. This funding amount, as well as a potential NSF contribution to operations at the requested level of $7.5 million, is contingent on an arrangement being negotiated that allows broad U.S. astronomical community access to survey products and competed observing time on a facility that should significantly enhance the U.S. scientific productivity of ALMA.

[24] The total construction cost is estimated to be $110 million, and so with a third share for the federal government CCAT falls in the "medium" cost category.

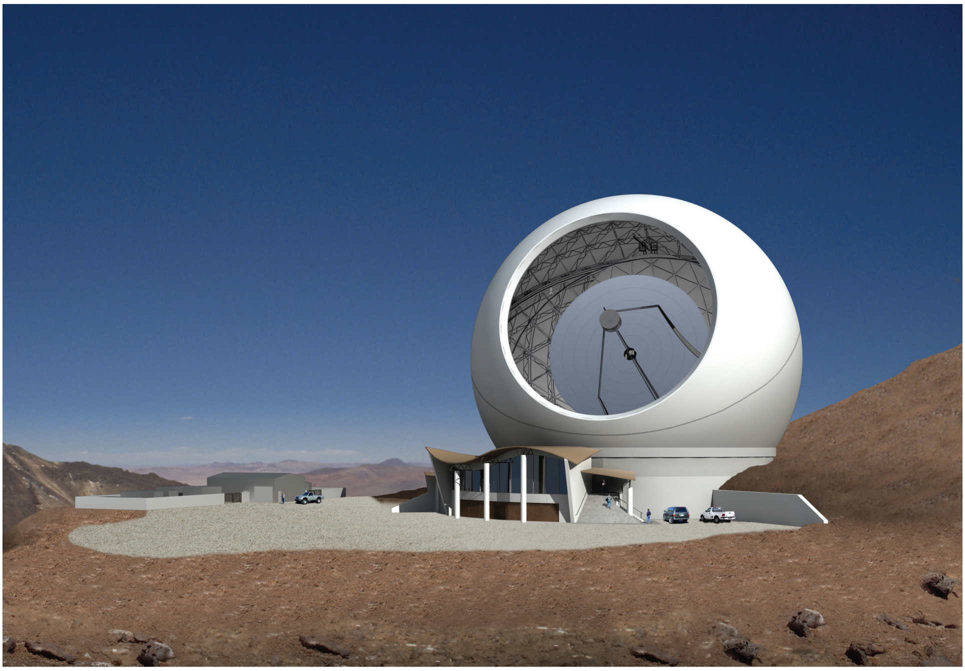

FIGURE 7.11 CCAT is a 25-meter telescope located at 18,500 feet elevation close to ALMA in Chile. The mirror surface has active control. CCAT will operate from 0.3 to 1.4 millimeters (with a goal of 0.2 to 3.5 mm) with a 10- to 20-arcminute field of view and diffraction-limited angular resolution of 10 × (wavelength in millimeters) arcsecond. Highly sensitive bolometer arrays with more than 10,000 sensors using superconducting transition edge sensor technology are envisaged. The flux sensitivity is limited by source confusion to around 1 mJy. SOURCE: M3 Engineering/CCAT/Caltech.

CCAT is called out to progress promptly to the next step in its development because of its strong science case, its importance to ALMA, and its readiness.

Small Additions and Augmentations to NSF's Core Research Program

As discussed in Chapters 5 and 6, several changes to NSF's core research program in ground-based astronomy are recommended. Collected here is an unranked list of the five components for which increases in funding are deemed most needed. Programs that are not mentioned are assumed to proceed with existing budgets, subject to senior review recommendations, although the committee emphasizes the importance of many small elements of the core research programs described in Chapter 5.

Advanced Technologies and Instrumentation

Competed instrumentation and technology development are supported, including computing at astronomical facilities in support of the research program, as described in Chapter 5. The current level of funding is roughly $10 million per year, and the survey's proposal is to increase this to $15 million per year to accommodate key opportunities including, especially, advanced technology in adaptive optics development and radio instrumentation.

Astronomy and Astrophysics Research Grants Program

Competed individual investigator grants, as described in Chapter 5, provide critical support for astronomers to conduct the research for which the observatories and instruments are built. The current funding level has fluctuated, especially because of the welcome injection of ARRA funding, but the rough baseline is $46 million per year. An increase of $8 million for a total of $54 million per year is recommended. This increment should include the support of new opportunities in Laboratory Astrophysics.

Gemini Augmentation

An international partnership supports operations and instrumentation at the two international Gemini telescopes. As described in Chapter 6, the imminent withdrawal of the United Kingdom from the partnership will require that additional support be provided by the remaining partners. Set against this need is a desire to operate the telescopes more efficiently and achieve significant savings in operations costs. An augmentation of $2 million to the annual budget is recommended subject to the results of NSF's exploring a restructuring of the management and operations of Gemini and acquiring an increased share of the observing time, as discussed in Chapter 6.

Telescope System Instrument Program

The TSIP trades competed support of telescope instrumentation on privately operated telescopes for competed observing time open to the entire U.S. astronomical community. As described in Chapter 6, this is a vital component of the OIR system that was instituted following advice presented in the 2001 decadal survey. It is currently supporting new telescope instrumentation at an average rate of roughly $2 million to $3 million per year and an increment to $5 million per year is recommended.

Theory and Computation Networks

A new competed program coordinated with a similar program proposed to NASA, Theory and Computation Networks will, as described in Chapter 5, support coordinated theoretical and computational attacks on selected key projects that feature prominently in the science program and are judged ripe for such attention. An NSF annual funding level of $2.5 million is recommended.

RECOMMENDATIONS FOR THE AGENCIES

The committee used a sandchart tool as an existence proof that its recommended phased program for each agency—NASA, DOE, and NSF—would fit within the suggested and envisioned decadal budget. It is recognized that budgets may indeed shift as the decade proceeds, relative to the committee's assumptions. Therefore, the charts are perceived as most useful for conveying the committee's intended staging of the different activities it has recommended.

NASA Astrophysics

The recommended program for NASA has been constrained to fit within an Astrophysics Division budget for the decade that is flat in FY2010 dollars. In round numbers, $3.7 billion is available for new initiatives and augmentations to existing programs within the 2012-2021 budget submissions. As indicated by the example shown in Figure 7.12, it is possible to accommodate the recommended program within the profile, launching WFIRST by the end of the decade; enhancing the Explorer program; getting a good start on LISA; carrying out the IXO, New Worlds, and Inflation Probe technology development programs; making essential augmentations to the core research program; and contributing to SPICA. Of course, there are many contingencies. For example, if LISA fails to satisfy either of the conditions specified by the survey committee, or if WFIRST, as recommended here, becomes a collaborative mission, it could be possible to accelerate IXO.

The committee was charged by NASA to consider a more conservative budget projection based on an extrapolation of the President's FY2011 budget submission that projects roughly $700 million less funding, or $3.0 billion available over the decade. In the event that insufficient funds are available to carry out the recommended program, the first priority is to develop, launch, and operate WFIRST and to implement the Explorer program and core research program recommended augmentations. The second priority is to pursue the New Worlds Technology Development Program, as recommended, to mid-decade review by a decadal survey implementation advisory committee (as discussed in Chapter 3), to start LISA as soon as possible subject to the conditions discussed above, and to invest in IXO

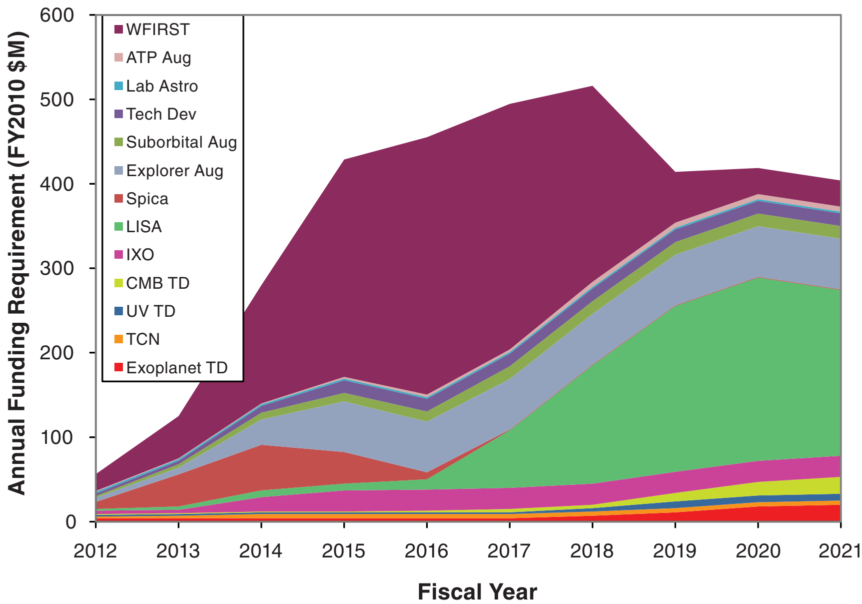

FIGURE 7.12 Astro2010-recommended program for NASA—example phasing. This sandchart is the outcome of a committee exercise carried out in FY2010 dollars to show that the phased program recommended would fit within the budget constraints adopted by the committee in developing its recommendations. The profiles and budget costs will vary on a project-by-project and program-by-program basis and should not be taken as representing a literal recommended program. The sandcharts are presented here to show, as an existence proof, that within a budget that is flat for the decade in FY2010 dollars the Astro2010-recommended new initiatives and program augmentations are implementable within NASA SMD spending limits.

technology development as recommended. The third priority is to pursue the CMB Technology Development Program, as recommended, to mid-decade review by a decadal survey implementation advisory committee. It is unfortunate that this reduced budget scenario would not permit participation in the JAXA-SPICA mission unless that mission's development phase is delayed.

NSF Astronomy

The proposed program for NSF has been constrained to fit within an NSF-AST budget doubling scenario, in which $500 million becomes available by 2021 for new activities and the annual NSF-AST budget rises to $325 million. As the example presented in Figure 7.13 shows, it is possible to fund early operations for LSST beginning in 2016, build up the Mid-Scale Innovations Program augmentation,

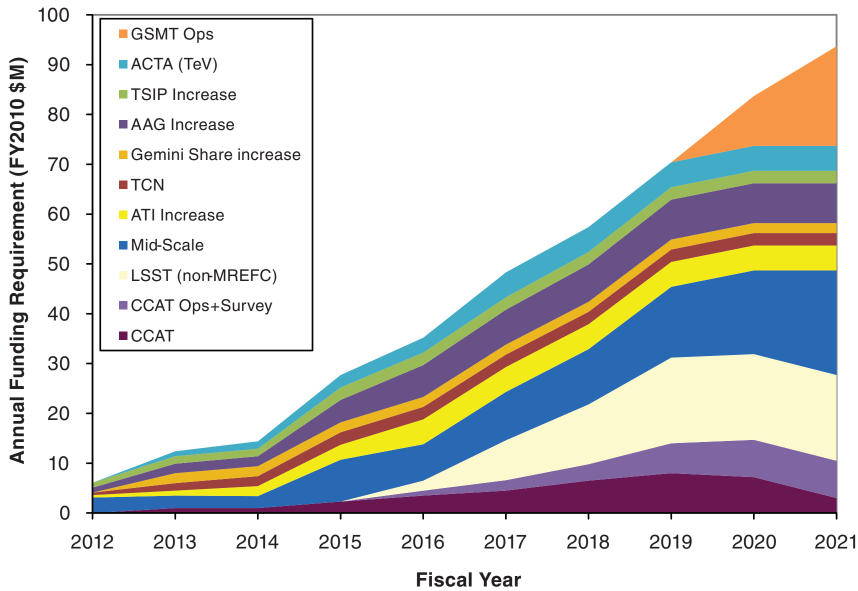

FIGURE 7.13 Astro2010-recommended program for NSF—example phasing. This sandchart is the outcome of a committee exercise carried out in FY2010 dollars to show that the phased program recommended would fit within the budget constraints adopted by the committee in developing its recommendations. The profiles and budget costs will vary on a project-by-project and program-by-program basis and should not be taken as representing a literal recommended program. The sand-charts are presented here to show, as an existence proof, that within a "doubling" budget over the decade the Astro2010-recommended new initiatives and program augmentations are implementable within NSF-AST spending limits.

complete CCAT, augment the core research program, and collaborate on ACTA. The timescale for starting to operate GSMT is quite uncertain, but this option can also be accommodated toward the end of the decade. As regards the sequencing of LSST and GSMT, in this and the two budget scenarios that follow, it is assumed that LSST would enter the MREFC process as soon as the budgets would allow and that GSMT would follow.

In the event that the realized budget is closer to an extrapolation of the president's FY2011 budget, that is, between the optimistic budget-doubling and the pessimistic flat-budget scenarios, the order of priority is to phase in the recommended core research program augmentations and the Mid-Scale Innovations Program together and at as fast a rate as the budget will allow, noting that the recommended Gemini augmentation is time-critical. LSST would receive an MREFC start and require NSF-AST operations funding beginning in 2016. NSF-AST support for GSMT operations and ACTA collaboration both would be delayed until funding becomes available.

If the realized budget is truly flat in FY2010 dollars, the implication is that, given the obligation to provide operational costs for the forthcoming ALMA and ATST, there is no possibility of implementing any of the recommended program this decade—without achieving significant savings through enacting the recommendations of the first 2006 senior review process and/or implementing a second more drastic senior review before mid-decade. Because the termination of programs takes time to implement in practice, it will be difficult to accrue significant new savings before the end of the decade. Thus, in practice, very few new activities could be started within NSF-AST.

DOE High Energy Physics

A program fitted under the DOE budget doubling scenario means that roughly $40 million per year would be available by the end of the decade, after due allowance for an underground dark matter detection program as recommended by HEPAP-PASAG. As indicated by the example shown in Figure 7.14, this amount will be sufficient to allow participation in LSST, WFIRST, and ACTA as well as some of the smaller astrophysical initiatives recommended by HEPAP-PASAG under Scenario C. In addition, a $2 million per year Theory and Computation Networks program is recommended.

However, if the budget is lower, the HEPAP-PASAG recommended investment in dark matter detection will be reduced and the available funds will decrease to $15 million under Scenario A. DOE is a minor partner in the two largest projects that the survey committee has recommended—LSST and WFIRST—and it is likely that the phasing will involve choices by NSF and NASA, respectively. Other considerations being equal, the recommended priority order is to collaborate first on LSST because DOE will have a larger fractional participation in that project, and its technical contribution is thought to be relatively more critical. ACTA, Theory and Computation Networks, and the smaller initiatives have lower priority.

EPILOGUE

This is an extraordinary time in astronomy. The scientific opportunities are without precedent—finding and characterizing other planets like Earth, tracing the history of the cosmos from the time of inflation to our own galaxy and solar system today, detecting the collisions of black holes across the universe, and testing the implications of Einstein's theories a century after they were formulated. The tools are becoming available to make giant strides toward deciphering the mysteries of the two primary components of the cosmos—dark energy and dark matter—and

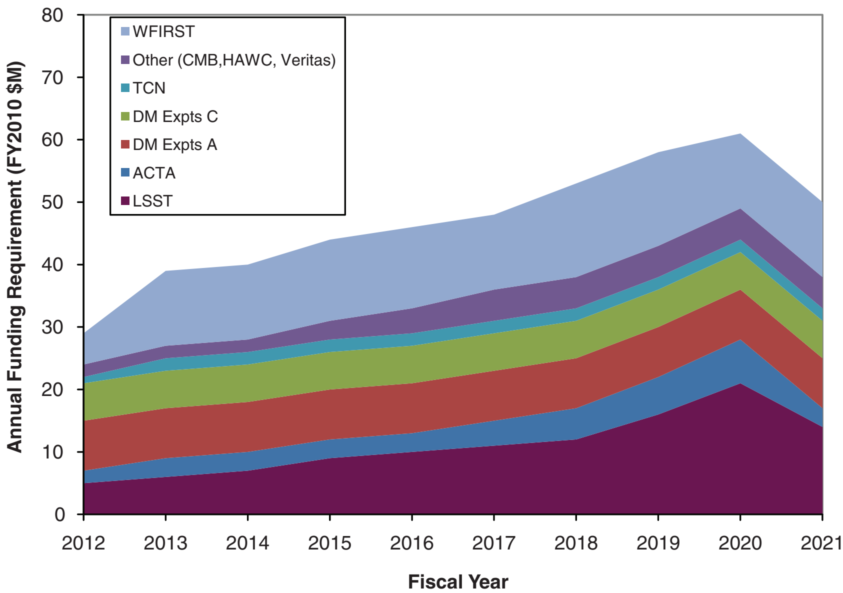

FIGURE 7.14 Astro2010-recommended program for DOE—example phasing. This sandchart is the outcome of a committee exercise carried out in FY2010 dollars to show that the phased program recommended would fit within the budget constraints adopted by the committee in developing its recommendations. The profiles and budget costs will vary on a project-by-project and program-by-program basis and should not be taken as representing a literal recommended program. The sandcharts are presented here to show, as an existence proof, that within a "doubling" budget over the decade the Astro2010-recommended new initiatives and program augmentations are implementable within DOE High Energy Physics spending limits.

toward discovering the prevalence of life in the universe. The discoveries that will be made will profoundly change our view of the cosmos and our place within it.

Astronomy, ever young, is vibrant and currently growing by attracting enthusiastic and skilled newcomers from other fields—particle physics, biology, chemistry, computer science, and nuclear physics—and traditional astronomers' professional horizons are enlarged by learning from them. This is truly a privileged time to be an astronomer.

Changes are apparent now in the way research is being done. It is more ambitious. And it is also more collaborative and more international, which enlarges the realm of what is achievable. This context complicates the task of preparing a strategic vision and necessitates a new fiscal, technical, and temporal realism at a time of constrained economic resources in the United States that will inevitably lead to a smaller fraction of the global research effort supported by the federal government.

The committee has been strategic in its thinking, crafting a program that optimizes the scientific return, building on previous public investment in astrophysics while making difficult choices in laying a foundation for the next decade.

The committee notes the unprecedented level of effort and involvement in this survey by the astronomical community, with hundreds of astronomers and astrophysicists attending town hall meetings, contributing white papers, and serving on panels. The vision put forth in this report is a shared vision.

Appendixes

A

Summary of Science Frontiers Panels' Findings

Five Science Frontiers Panels (SFPs) were appointed by the National Research Council as part of the first phase of the decadal survey on astronomy and astrophysics. The SFPs were charged to identify and articulate the scientific themes that will define the frontier in astronomy and astrophysics research in the 2010-2020 decade. Each panel was asked to prepare a report that would identify the scientific drivers of the field and the most promising opportunities for progress in research in the next decade, taking into consideration those areas where the technical means and the theoretical foundations are in place for major steps forward. More broadly, each panel was charged with the following tasks:

- Identify new scientific opportunities and compelling scientific themes that have arisen from recent advances and accomplishments in astronomy and astrophysics;
- Describe the scientific context of the importance of these opportunities, including connections to other parts of astronomy and astrophysics and, where appropriate, to the advancement of our broader scientific understanding;
- Describe the key advances in observation and theory necessary to realize the scientific opportunities within the decade 2010-2020; and
- Considering the relative compelling nature of the opportunities identified and the expected accessibility of the measurement regimes required, call out up to four central questions that are ripe for answering and one general area where there is unusual discovery potential and that define the scientific frontier of the next decade in the SFP's subfield of astronomy and astrophysics.

Each Science Frontiers Panel provided its inputs to the survey committee in the Spring of 2009 and completed its panel report thereafter. The SFP reports are provided in the second volume of the decadal survey, along with the reports of the Program Prioritization Panels.[1]

The five SFPs and their scientific scopes were as follows:

- *Panel on Cosmology and Fundamental Physics* (CFP). The CFP scope encompassed cosmology and fundamental physics, including the early universe, the microwave background, the reionization and galaxy formation up to virialization of protogalaxies, large-scale structure, the intergalactic medium, the determination of cosmological parameters, dark matter, dark energy, tests of gravity, astronomically determined physical constants, and high-energy physics using astronomical messengers.
- *Panel on the Galactic Neighborhood* (GAN). The GAN scope encompassed the galactic neighborhood, including the structure and properties of the Milky Way and nearby galaxies, and their stellar populations and evolution, as well as interstellar media and star clusters.
- *Panel on Galaxies Across Cosmic Time* (GCT). The GCT scope encompassed galaxies across cosmic time, including the formation, evolution, and global properties of galaxies and galaxy clusters, as well as active galactic nuclei and quasi-stellar objects, mergers, star-formation rate, gas accretion, and supermassive black holes.
- *Panel on Planetary Systems and Star Formation* (PSF). The PSF scope encompassed planetary systems and star formation, including solar system bodies (other than the Sun) and extrasolar planets, debris disks, exobiology, the formation of individual stars, protostellar and protoplanetary disks, molecular clouds and the cold interstellar medium, dust, and astrochemistry.
- *Panel on Stars and Stellar Evolution* (SSE). The SSE scope encompassed stars and stellar evolution, including the Sun as a star, stellar astrophysics, the structure and evolution of single and multiple stars, compact objects, supernovae, gamma-ray bursts, solar neutrinos, and extreme physics on stellar scales.

Table A.1 shows the final science questions and areas of discovery potential as described in the SFP reports.

[1] National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2011.

TABLE A.1 Summary of Science Frontiers Panels' Findings

Panel	Science Questions		Area(s) of Unusual Discovery Potential
Cosmology and Fundamental Physics	CFP 1	How did the universe begin?	Gravitational Wave Astronomy
	CFP 2	Why is the universe accelerating?	
	CFP 3	What is dark matter?	
	CFP 4	What are the properties of neutrinos?	
Galactic Neighborhood	GAN 1	What are the flows of matter and energy in the circumgalactic medium?	Time-Domain Astronomy Astrometry
	GAN 2	What controls the mass-energy-chemical cycles within galaxies?	
	GAN 3	What is the fossil record of galaxy assembly from the first stars to the present?	
	GAN 4	What are the connections between dark and luminous matter?	
Galaxies Across Cosmic Time	GCT 1	How do cosmic structures form and evolve?	The Epoch of Reionization
	GCT 2	How do baryons cycle in and out of galaxies, and what do they do while they are there?	
	GCT 3	How do black holes grow, radiate, and influence their surroundings?	
	GCT 4	What were the first objects to light up the universe, and when did they do it?	
Planetary Systems and Star Formation	PSF 1	How do stars form?	Identification and Characterization of Nearby Habitable Exoplanets
	PSF 2	How do circumstellar disks evolve and form planetary systems?	
	PSF 3	How diverse are planetary systems?	
	PSF 4	Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?	
Stars and Stellar Evolution	SSE 1	How do rotation and magnetic fields affect stars?	Time-Domain Surveys
	SSE 2	What are the progenitors of Type Ia supernovae and how do they explode?	
	SSE 3	How do the lives of massive stars end?	
	SSE 4	What controls the mass, radius, and spin of compact stellar remnants?	

B

Summary of Program Prioritization Panels' Recommendations

Important input to the work of Astro2010 was provided by the work of the four National Research Council-appointed Program Prioritization Panels (PPPs):

- Panel on Electromagnetic Observations from Space (EOS),
- Panel on Optical and Infrared Astronomy from the Ground (OIR),
- Panel on Particle Astrophysics and Gravitation (PAG), and
- Panel on Radio, Millimeter, and Submillimeter Astronomy from the Ground (RMS).

The PPPs were charged to identify and recommend a prioritized program of federal investment in research activities in the program areas indicated by the panel names:

- Space-based electromagnetic observations of astrophysical phenomena;
- Observations of astrophysical phenomena primarily by means of optical and infrared measurements from the ground;
- Exploration of areas at the interface of physics and astronomy such as gravitational radiation and TeV gamma-ray astronomy, and with free-flying space missions testing fundamental gravitational physics; and
- Observations of astrophysical phenomena primarily by means of measurements from the ground in the radio, millimeter, and submillimeter portions of the electromagnetic spectrum.

In formulating its conclusions, each PPP was charged to draw on several sources of information: (1) the science forefronts identified by the Astro2010 Science Frontiers Panels, (2) input from the proponents of particular research activities, and (3) independent cost and technical readiness assessments. The panels' recommendations were integrated into a program for all of astronomy and astrophysics by the Astro2010 Committee for a Decadal Survey of Astronomy and Astrophysics. In particular, each PPP was charged to:

- Report on the status of existing research activities to set the context for future research activities, incorporating findings of the survey's Infrastructure Study Groups.
- Preview and compare proposed research activities, including those carried forward from previous surveys that have not been given a formal construction start.
- State the relative importance of (1) smaller projects and generic research programs that involve competitive peer review and (2) programs that leverage public and private infrastructure investments, where appropriate.
- Assess and describe the best available estimates of the construction costs and lifetimes for each recommended research activity together with their full running costs (operations, science, and upgrades).
- Identify particular risks for each research activity that would adversely affect the projected cost, technical readiness, or schedule of the activity. Identify those factors that could change an activity's priority and/or scope.
- Informed by (1) the recommendations of the Science Frontiers Panels and (2) the panel's own research activity assessments, recommend a prioritized, balanced, and integrated research program that includes a rank ordering of research activities and a balanced technology development program.

A preliminary PPP-recommended program was used to identify activities that were then subjected to an independent cost appraisal and technical evaluation (CATE). Each panel's final recommendations to the Astro2010 survey committee included consideration of the CATE results. Each PPP provided the committee with an interim internal and confidential summary report of its recommended program in the Fall of 2009 and submitted its complete panel report thereafter. The PPP reports are included in the second volume of the decadal survey, along with the reports of the Science Frontiers Panels.[1]

The main results from the four PPPs are summarized in Table B.1.

[1] National Research Council, *Panel Reports—New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., 2011.

TABLE B.1 Summary of Priority Activities as Recommended by the Program Prioritization Panels

EOS Panel		PAG Panel		RMS Panel		OIR Panel	
Priority Activity	Cost Appraisal (category)	Priority Activity	Cost Appraisal (category)	Priority Activity	Cost Appraisal (category)	Priority Activity	Cost Appraisal (category)
(1) WFIRST	$1.5 billion (L)	(1) LISA	$1.5 billion (L)	(1) HERA-I and HERA-II	$25 million + $85 million (M)	(1) GSMT	≥$1 billion (L)
(2) IXO (project start)	$1.0 billion (L)	(2) ACTA (AGIS)	$0.2 billion (L)	(2) FASR (2) CCAT	$100 million (M) $110 million (M)	(2) LSST	$460 million (L)
(3) Exoplanet Mission	$0.7 billion (L)	(1) Pulsar Timing Array for Gravitational Wave Detection	$70 million (M)	ATA enhancement	$44 million (M)	(1) NSF medium-scale instrumentation program augmentation (OIR+PAG+RMS)	$200 million
(1) BLISS	$0.2 billion (M)	(1) NASA Explorer augmentation	$1 billion (M)	Enhancements to GBT, EVLA, VLBA, ALMA	$120 million	(2) TSIP augmentation	$40 million (M)
				Enhancements to CARMA, EHT	$25 million		
(2) Explorer	$0.5 billion (M)	(2) Technology development augmentation and ULDB R&D and augmentation	$550 million NASA (M), $150 million NSF plus DOE (M)	—	—	(2) OIR system augmentation	$61 million (M)
(3) R&A	$0.2 billion (M)	(3) Auger North	$60 million (U.S. portion) (M)	—	—	Small, unprioritized programs	$100 million

NOTE: Entries under each panel are in priority order within size category. Note that the RMS panel has two equal second priorities. The EOS costs are shown for the panel's enhanced budget scenario. The tabulated costs are in FY2010 dollars and are estimates for the decade. Categories: L, large; M, medium.

C

The Cost, Risk, and Technical Readiness Evaluation Process

In response to the statement of task, an independent cost appraisal and technical evaluation (CATE) process was established for the projects considered for recommendation in this report. Implementation of the CATE process was performed by an experienced competitively selected contractor, the Aerospace Corporation, using a process operating in parallel with the committee process described in Chapter 7. The objective of the CATE process was to judge the readiness, technical risk, and schedule risk for the activities under consideration. Schedule estimates and cost appraisals were developed for each activity. While past surveys have focused solely on the cost, the current survey committee believes that this number, although important, is only part of the story. Moreover, cost estimates for projects at an early stage of development are inherently less certain because not all the design requirements have been specified and not all technical risks have been retired.

For consistency and ease of comparison, the CATE reports for space missions give an appraised program cost in FY2010 dollars. The cost threshold for the CATE process was established at approximately $350 million at NASA and approximately $75 million for NSF and DOE. The Committee for a Decadal Survey of Astronomy and Astrophysics developed a cost-spreading tool separate from the CATE process using a 3 percent per annum base inflation rate over the decade, to develop some notional funding profiles against possible agency funding wedges. The comparison of required funding profiles with future agency budgets was done, the committee believes, in as realistic a manner as possible, although it recognizes the considerable uncertainties in both summed needs of the recommended projects and in the funding available in the future.

The parallel implementation of the committee and CATE processes, shown in Figure 7.1, allowed for timely and efficient data gathering and fact finding by the CATE contractor and the committee while maintaining the independence of each activity. As one of the first activities of the survey, before the CATE process was fully developed, the committee solicited Notices of Intent (NOI) to gauge the kinds of research activities it could expect to have to assess during the course of the survey. This first step was followed by receipt of white papers and then two request-for-information cycles (RFI-1 and RFI-2), resulting in multiple submittals from candidate activities. The output of the RFI-2 process was the selection of candidates to be put forward for detailed CATE process analysis. The proposed candidates were selected by the Program Prioritization Panels (PPPs) based on scientific priorities together with a scientific evaluation of the technical approaches. The candidates were approved by the committee.

The CATE component of the process was iterative in the early stages, starting with a technical evaluation of the selected candidates and then proceeding to follow-up questions to individual project teams as required. The CATE and survey processes were linked, through direct communication between the contractor and committee and panel members, as well as presentations to the committee and PPPs. The interactions focused on ensuring the quality of the assessments by the contractor and engaging the technical expertise of the panels and the committee. Discussions between the PPPs and the cost contractor were essential to ensure that project details were not misinterpreted by the contractor. Intermediate results were then presented to the full committee in October 2009 at the committee's fourth meeting, followed by several more iterative steps focused on reviewing the final assessments and appraisals for accuracy, realism, and consistency by the committee.

Despite the considerable interaction with the committee and panels, the survey process maintained the independence of the contractor so that its final analysis was free from undue influence by either the committee itself or by interests outside the survey. This independence was accomplished by establishing the contractor as a consultant to the National Research Council rather than a direct participant in the committee effort. Therefore, although the committee worked closely with the contractor to provide technical inputs as requested, as well as expert review and commentary, the final result was accepted and certified as independent work performed by the contractor alone. Equally important to the independence of the contractor was the committee's responsibility for reviewing the contractor's work and exercising its judgment in accepting the contractor's results.

A second essential consideration affecting the CATE process was the recognition that ground-based and space-based systems are fundamentally different with respect to how they are funded and developed. This disparity profoundly influenced the methods by which the ground and space systems were evaluated and validated by the contractor. The space-based systems were evaluated statistically using the process presented in Figure C.1. This process utilized an extensive database available to the contractor from many past projects performed by NASA and an associated array of experienced support contractors. Thus, despite some mission-unique elements, the size and scale of the space projects were well within the experience base of the contractor and the parametric model employed for the analysis by the contractor.

Ground-based systems required a different treatment since they are typically developed by a consortium consisting of universities and/or federally funded agencies with an associated mix of government and private funds. Management and review of these activities involve unique institutionally driven processes compared to space-based activities. A relevant cost and schedule database for past large ground-based projects is largely nonexistent. Furthermore, the size and cost for large ground projects have approached those being built for space only in the past decade. Each of the ground-based projects evaluated in the CATE process required an extrapolation from existing facilities using key discriminating factors following the process shown in Figure C.2.

Because the available database for ground projects did not support a parametric analysis as used for the space projects, a bidirectional analysis was employed. A project's own bottom-up costs were assessed by the contractor in consultation with the committee and panels. Once this first element was completed, the contractor then identified the specific discriminating elements requiring cost or schedule analogies and extrapolation. Further information was requested of the activities being assessed when information gaps were identified. This approach was considered by the committee to be the most appropriate method for achieving a realistic cost estimate for the ground projects, and it was successful as demonstrated by the contractor's being able to provide an assessment of technical readiness, risk, and cost within the

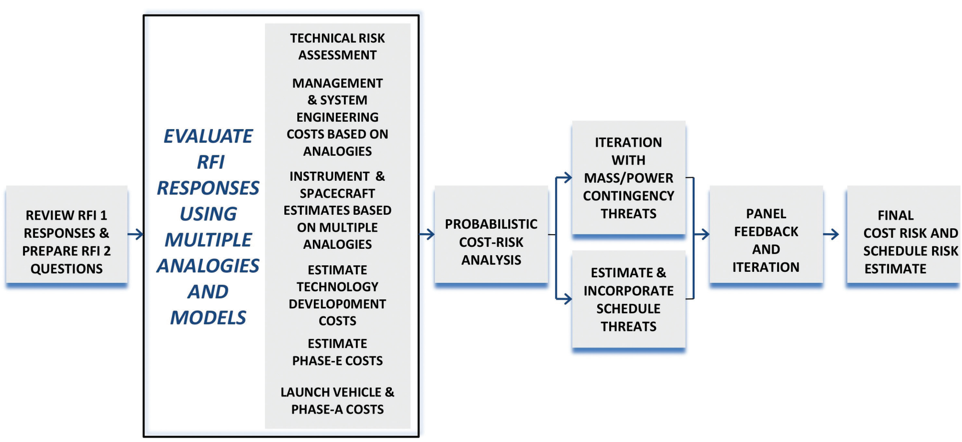

FIGURE C.1 CATE process for space-based projects.

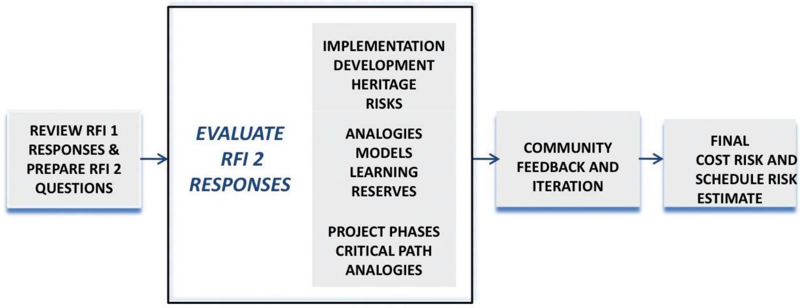

FIGURE C.2 CATE process for ground-based projects.

following limitations. The contractor had no independent basis for evaluating the operations costs estimates provided for any ground-based project. Those appraisals were constructed by the survey committee on the basis of project input and the experience and expertise of its members. For some projects, the data supplied by the projects was insufficient for the contractor to do a robust independent cost evaluation. Instead, the evaluation was limited to technical readiness and risk, as well as identifying those elements of the projects that drive the risks. Productive interactions between the contractor and the panels clarified a number of issues.

As would be expected, the cost appraisal process is highly dependent on both the maturity of the project design and the detail and quality of the available technical information. Overall, the detail of the RFI-2 inputs was excellent, although the majority of the projects evaluated were at a Pre-Phase-A stage of development. In the case of space projects, the dominant cost elements of the space projects are the instruments (20 percent), spacecraft system (12 percent), cost reserves (19 percent), and mission threat elements (18 percent), corresponding to approximately 70 percent of the total mission cost. The threats corresponding to mass and power, launch vehicle, and schedule were quantitatively evaluated by the committee at a general level and then tailored as to how they were applied to specific missions. Ground projects typically were found to have shorter development schedules than might be realistic and smaller cost reserves than might be prudent.

Because of the immaturity of some of the proposed activities, cost uncertainties are higher than typical for activities moving into development either via NSF's MREFC process or at the preliminary design review stage for NASA and DOE. The committee worked with the contractor to develop an acceptable set of quantitative metrics that could be used to fairly calculate the probable delta cost driven by the assessed maturity of each mission. These metrics included estimation of growth of applicable system resources such as power and mass along with mission-specific factors.

The end result of the incorporation of cost uncertainties is the cost histogram shown in Figure C.3 for the JDEM-Omega (similar to WFIRST), LISA, and IXO missions. The cost uncertainties are shown as "threats" in the figure. The incorporation of threats and risks resulted in the CATE cost totals averaging 55 percent higher than the projects reported based on NASA estimates. The associated S-curves are shown in Figure C.4. An S-curve represents the cumulative probability that a project will be completed at the given total cost. The NASA cost estimates came in at approximately the 10 to 15 percent point on the S-curve representing the statistically derived CATE cost for the same mission. Based on historical metrics, it would be expected that the NASA estimates would grow to approximately 30 to 50 percent on the S-curve at end of mission formulation unless efforts are made to descope or simplify the mission concepts.

The costs shown in Figures C.3 and C.4 for the JDEM-Omega, LISA, and IXO missions represent the full cost to NASA without consideration of ESA participation. The contractor also developed a cost metric for a notional 50-50 NASA-ESA joint program incorporating a 25 percent "foreign participation" penalty based on an assessment of similar missions. Figure C.5 shows the resulting cost to NASA with a comparison of the 100 percent and 50 percent participation shares. Note

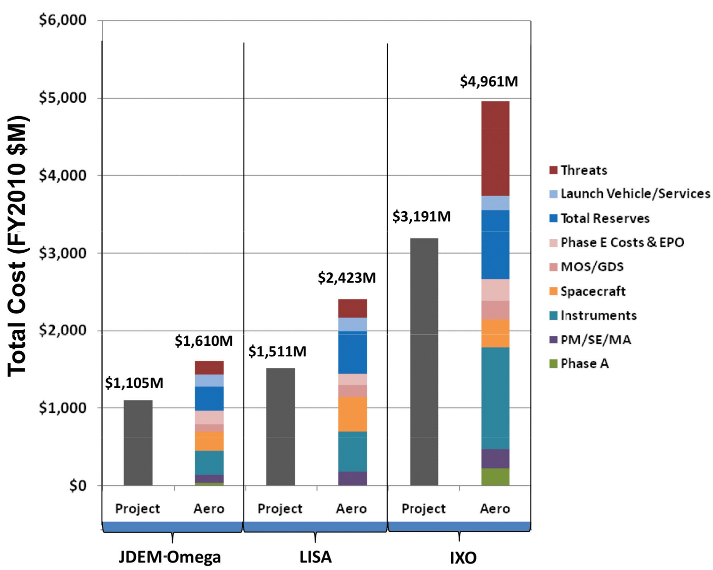

FIGURE C.3 Project estimate compared with contractor (Aerospace Corporation) appraisal of program costs for JDEM-Omega, LISA, and IXO. Costs shown are for the full mission, including Phase A, and are in FY2010 dollars. Contractor appraisals of cost are by work breakdown structure element. EPO, education and public outreach; MOS/GDS, mission operation system/ground data system; PM/SE/MA, program management/system engineering/mission assurance.

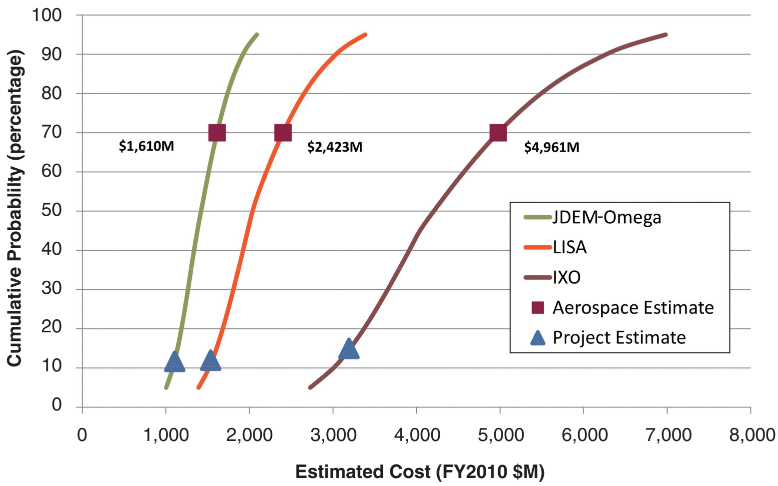

FIGURE C.4 Program S-curve cost comparison. Costs match those presented in Figure C.3. Project estimates reflect a 10 to 15 percent probability that the project will be completed at that low a cost. Costs are in FY2010 dollars and represent results of the survey's CATE process as described.

	JDEM Omega		LISA		IXO	
$FY10	100% NASA	50% NASA	100% NASA	50% NASA	100% NASA	50% NASA
Phase A	$44	$44	$11	$11	$223	$223
Development Cost B-D	$1,197	$748	$2,052	$1,283	$3,890	$2,431
Launch Vehicle	$154	$77	$187	$94	$523	$261
Phase E	$215	$108	$172	$86	$326	$163
Total Cost	$1,610	$976	$2,423	$1,473	$4,961	$3,078

$FY10	100% NASA	50% NASA
Total All Three	$8,993	$5,528
JDEM Omega & LISA	$4,032	$2,450
JDEM Omega & IXO	$6,571	$4,055
LISA & IXO	$7,384	$4,551

FIGURE C.5 Cost estimate for 100 percent versus notional 50 percent cost division between NASA and ESA for the JDEM-Omega, LISA, and IXO missions. Costs shown include a penalty of approximately 25 percent for foreign participation. Costs are in FY2010 dollars.

that the 50 percent number shown in Figure C.5 does not reflect a perfect 25 percent penalty factor due to some minor variances in the cost distribution for the individual missions.

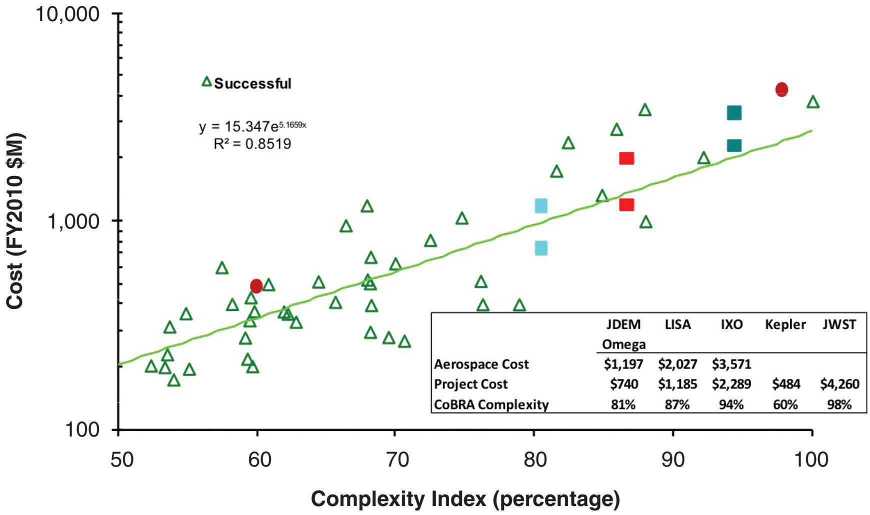

FIGURE C.6 JDEM-Omega, LISA, and IXO missions plotted on complexity versus cost curve for 40 analogous missions shown as triangles. The green line represents the mean value for the 40 missions. The solid red circles show the relative positions of the Kepler and JWST missions, which are used as anchoring end points of known complexity and approximate cost. The paired upper and lower solid squares represent the contractor CATE cost appraisal versus the project estimate, respectively, for JDEM-Omega, LISA, and IXO. Note that the costs shown do not match those shown in Figures C.4 and C.5, because the costs for Phase A, technology development, Phase E, launch vehicle, and launch vehicle threats were removed to allow for direct comparison of the three missions with recent and historical missions of similar scope. Costs are in FY2010 dollars.

Once the CATE effort was complete, an independent validation of the cost estimates was performed using the Complexity Based Risk Assessment (CoBRA) tool developed by Aerospace Corporation (schedule evaluations were also performed but are not presented). Figure C.6 shows the mapping of the three space mission candidates, JDEM-Omega, LISA, and IXO, on a plot representing the results of approximately 40 analogous successful missions (indicated by green triangles).

The results show excellent correlation with each other and with the existing mission data set, indicating that the contractor estimates compare favorably with the costs of other successful missions of similar complexity. As would be expected, the 70 percent point is above the average (designated by the green line), basically representing the 50 percent mean for the data set. Similarly the NASA estimates fall near or below the mean, which is consistent with the S-curve results discussed above. This plot supports the conclusion that the contractor costs are reasonable and represent a realistic 70 percent confidence estimate based on the information provided for the assessment.

D

Mid-Scale Project Descriptions

This survey received 29 proposals that would be eligible for competition, with an aggregate construction or fabrication cost of roughly $1.2 billion. The Program Prioritization Panels recommended a subset of these very highly, at a rough total cost of $400 million. It is not appropriate for this survey to make priority assessments for activities that would compete in a peer-reviewed program. However, the case for such a program line is best made by describing selected examples, as is done below in alphabetical order and in Table 7.1. Not all of them will be funded, but the funding recommended would be sufficient to proceed with many of them, as well as several excellent new proposals that will surely be submitted in response to a general solicitation. These proposals are grouped into three cost categories based on submitted descriptions and not an independent committee review. It is important that the Mid-Scale Innovations Program itself maintain a balance between large and small projects.

$40 MILLION TO $120 MILLION RANGE

Big Baryon Oscillation Spectroscopic Survey. The Big Baryon Oscillation Spectroscopic Survey (BigBOSS) would utilize the Kitt Peak National Observatory 4-meter Mayall telescope and a newly built optical spectrograph capable of measuring more than 5,000 spectra simultaneously over a 3-degree field of view. The science goal is understanding the acceleration of the universe by observing the distributions of 30 million galaxies and a million quasars. These data will also address important questions concerning the formation and evolution of galaxies, black holes, and the intergalactic medium.

Frequency Agile Solar Radiotelescope. The Frequency Agile Solar Radiotelescope (FASR) consists of three arrays of radio telescopes operating across a broad range of frequency (from 50 megahertz to 20 gigahertz). Its overall scientific program is to conduct time-domain mapping of the solar atmosphere in a campaign mode, delivering data products to the solar physics community. These will be used to study the nature and evolution of the Sun's magnetic field, to understand solar flares, improve the ability to predict "space weather" caused by solar activity, and better understand the quiet sun.

Hydrogen Epoch of Reionization Array. The Hydrogen Epoch of Reionization Array (HERA) is a multistage project in radio astronomy to understand how hydrogen is ionized after the first stars start to shine. The first phase (HERA I) is under way and will demonstrate the feasibility of the technical approach. The second phase (HERA II) would serve as a pathfinder for an eventual worldwide effort in the following decade to construct a facility with a total collecting area of a square kilometer and the power to make detailed maps of this critical epoch in the history of the universe. Proceeding with HERA II should be subject to HERA I meeting stringent performance requirements in its ability to achieve system calibration and the removal of cosmic foreground emission.

North American Nanohertz Observatory for Gravitational Waves. The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) would utilize the naturally occurring population of precision astronomical "clocks" called pulsars (rapidly spinning neutron stars) to detect very low frequency gravitational waves using upgraded capabilities of the existing Arecibo and Robert Byrd radio telescopes. The pulsar timing should also be able to detect the formation and collision of massive black holes with signals at periods of months to several years. This facility might even be able to detect relic gravitational waves from the very early universe (which is otherwise inaccessible to direct observations).

$12 MILLION TO $40 MILLION RANGE

Cosmic Microwave Background Initiatives. NSF has invested wisely in the past in ground-based telescopes that have considerably advanced the understanding of the fluctuations, polarization, and distortion of the cosmic microwave background through the Sunyaev-Zeldovich effect and gravitational lensing in a way that has complemented the suborbital and space program especially by working at smaller angular scales. Thanks to the development of new detector technology, ground-based observations are likely to remain highly competitive over the coming decade. The largest challenge to these observations is to detect the B-mode polarization that may be associated with very long wavelength gravitational radiation that was set down during the epoch of inflation.

Exoplanet Initiatives. The discovery and the study of exoplanets are developing at an extraordinarily rapid pace. It will be important to make strategic investments in new ground-based capabilities during the coming decade. One important component will be the aggressive development of ground-based high-precision radial velocity surveys of nearby stars at optical and near-infrared wavelengths (including efforts to determine the effects of stellar activity on these measurements). These surveys will need new spectrometers and significant time allocation on 8- to 10-meter-class telescopes. Another possibility is the development of ground-based high-spatial-resolution techniques in an exoplanet context for direct and indirect detection, and a third, facilities dedicated to surveying exozodiacal dust around nearby stars from the ground.

Next-Generation Adaptive Optics Systems. The adaptive optics technique can correct the distortions that are introduced by turbulence in Earth's atmosphere in images taken with ground-based telescopes. This technique enables near-infrared images to be obtained with resolution superior to that provided by the Hubble Space Telescope. The next generation of such systems deployed on the existing 8- to 10-meter telescopes will offer major improvements in the quality and wavelength coverage of the images, and in the fraction of the sky accessible to adaptive optics.

Next-Generation Instruments for Solar Telescopes. The Advanced Technology Solar Telescope (ATST) is currently in the MREFC construction queue. The Mid-Scale Innovations Program would be one avenue for providing a second generation of instruments for this facility and maintaining its cutting-edge capabilities.

$4 MILLION TO $12 MILLION RANGE

High Altitude Water Čerenkov Experiment. The High Altitude Water Čerenkov experiment (HAWC), sited in Mexico, is proposed to map the sky at gamma-ray energies above 1 TeV and detect transient sources. With its very large field of view, it will complement the proposed atmospheric Čerenkov facility.

E

Statement of Task and Scope

STATEMENT OF TASK

- The Committee on Astro2010 will survey the field of space- and ground-based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010-2020.
- The principal goals of the study will be to carry out an assessment of activities in astronomy and astrophysics, including both new and previously identified concepts, and to prepare a concise report that will be addressed to the agencies supporting the field, the congressional committees with jurisdiction over those agencies, the scientific community, and the public.

SCOPE

The subject matter of the survey will include experimental and theoretical aspects of observations of the cosmos, analysis of those observations, the theoretical framework for understanding the observations, and the professional infrastructure that enables the observations. Science that involves in situ observations for instance planetary or helio probes will be excluded.

The extent of the common ground between fundamental physics and cosmology has grown, and the strength of the relationship between physics questions at the quantum size scale and at the scale of the entire universe is becoming increasingly clear. The survey will treat this and other areas of interface with adjacent scientific disciplines, as appropriate.

Ground-based laboratory experimental data, physics-based theoretical models, and numerical simulation play a growing role in the interpretation of astronomical observations. The scope of the study will reflect these trends. The study will review the federal research programs that support work in the field, including the astrophysics program at the National Aeronautics and Space Administration (NASA), the astronomy program at the National Science Foundation (NSF), and selected aspects of the physics programs at the NSF and the Department of Energy (DOE). For the purpose of this charge, "activities" include any project, telescope, facility, mission, or research program of sufficient scope to be identified separately in the final report. The selection of subject matter will be guided by the content of these programs. Only physics topics with a strong overlap with astronomy and astrophysics will be treated. Solar astronomy will be covered, but space-based solar astronomy projects will not be prioritized.

The study will assess the infrastructure of the field, including research and analysis support; the educational system; instrumentation and technology development; data distribution, analysis, and archiving; theory programs; and so on. The committee will determine whether the optimal infrastructure necessary to advance the science and to capture the value of major activities is in place.

In its assessment, the committee will also consider the importance of balance within and among the activities sponsored by the various agencies that support research in astronomy and astrophysics. It will explore the diversity of the portfolio of activities ranging from principal-investigator-led research, through small, medium-sized, and large projects. The committee will conduct a review of relevant activities of other nations and the opportunities for joint ventures and other forms of international cooperation. It will also explore prospects for combining resources—private, state, federal, and international—to build the strongest possible set of activities for U.S. astronomy and astrophysics.

APPROACH

The committee will address the future of U.S. astronomy and astrophysics by formulating a decadal research strategy with recommendations for initiatives in priority order within different categories (related to the size of activities and their home agencies). In addition to reviewing individual initiatives, aspects of infrastructure, and so on, the committee will take a comprehensive look at the U.S. astronomy and astrophysics program and make a judgment about how well the program addresses the range of scientific opportunities and how it might be optimized. The guiding principle in developing the decadal research strategy and the priorities will be maximizing future scientific progress.

In contrast to previous surveys of the field, in view of the number of previously recommended but unrealized projects, the prioritization process will include those unrealized projects, and it will not be assumed that they will go forward. Projects that are sufficiently developed in terms of engineering design and technology development to have been given a formal start by the sponsoring agency would not, in general, be subject to reprioritization.

In determining the status of activities that are candidates for prioritization, the committee will review the technical readiness of the components and the system, it will assess various sources of risk, and it will develop its own estimate of the costs of the activity with help from an independent contractor with expertise in this area. It will not uncritically accept estimates provided by activity proponents or the agencies. It is anticipated that, on the basis of the technical readiness assessment, some initiatives may take the form of high-priority development programs rather than projects. In proposing a decadal U.S. research strategy for astronomy and astrophysics, the committee is expected to consider and make recommendations relating to the allocation of future budgets and address choices that may be faced, given a range of budget scenarios. For each prioritized activity, the committee will establish criteria on which its recommendations depend. The committee will make recommendations to the agencies on how to rebalance programs within budgetary scenarios upon failure of one or more of the criteria.

In addressing the U.S. effort in astronomy and astrophysics, the committee is expected to make recommendations bearing on the organization of research programs in astronomy within the current federal agency structure.

F

Acronyms

2MASS	2 Micron All Sky Survey
AAAC	Astronomy and Astrophysics Advisory Committee
AAAS	American Association for the Advancement of Science
AAG	Astronomy and Astrophysics Research Grants
AANM	*Astronomy and Astrophysics in the New Millennium*
AAPF	Astronomy and Astrophysics Postdoctoral Fellows
AAS	American Astronomical Society
ACS	Advanced Camera for Surveys
ACTA	Atmospheric Čerenkov Telescope Array
AGIS	Advanced Gamma-ray Imaging System
AGU	American Geophysical Union
ALFA	Adaptive optics with a Laser for Astronomy
ALMA	Atacama Large Millimeter/submillimeter Array
ALTAIR	Access to Large Telescopes for Astronomical Instruction and Research
AO	adaptive optics
AO	Announcement of Opportunity
APRA	Astronomy and Physics Research and Analysis
APS	American Physical Society
ARCADE	Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission
ARISE	Advanced Radio Interferometry between Space and Earth

ARO	Arizona Radio Observatory
ARRA	American Recovery and Reinvestment Act
ATA	Allen Telescope Array
ATI	Advanced Technologies and Instrumentation
ATP	Astrophysics Theory Program
ATST	Advanced Technology Solar Telescope
AUI	Associated Universities, Inc.
AURA	Association of Universities for Research in Astronomy
BigBOSS	Big Baryon Oscillation Spectroscopic Survey
BLISS	Background-Limited Infrared-Submillimeter Spectrograph
BPA	Board on Physics and Astronomy
CANGAROO	Collaboration of Australia and Nippon (Japan) for a Gamma Ray Observatory in the Outback
CARMA	Combined Array for Research in Millimeter-wave Astronomy
CATE	cost appraisal and technical evaluation
CFP	Cosmology and Fundamental Physics, Panel on
CMB	cosmic microwave background
COBE	Cosmic Background Explorer
CoBRA	Coherent Online Baseband Receiver for Astronomy
Con-X	Constellation-X
COROT	Convection, Rotation and Planetary Transits
CSO	Caltech Submillimeter Observatory
CTA	Čerenkov Telescope Array
CTIO	Cerro Tololo Inter-American Observatory
CXC	Chandra X-ray Observatory Center
DES	Dark Energy Survey
DOE	Department of Energy
DSIAC	decadal survey implementation advisory committee
E-ELT	European Extremely Large Telescope
EHT	Event Horizon Telescope
EJSM	Europa Jupiter System Mission
EOS	Electromagnetic Observations from Space, Panel on
ESA	European Space Agency
ESM	Electromagnetic Spectrum Management
ESO	European Southern Observatory
EU	European Union
EVLA	Expanded Very Large Array

EXIST	Energetic X-ray Imaging Survey Telescope
FACA	Federal Advisory Committee Act
FASR	Frequency Agile Solar Radiotelescope
FFAR	Federal Funding of Astronomical Research
FGST	Fermi Gamma-ray Space Telescope
FIRST	Faint Images of the Radio Sky at Twenty-one Centimeters
FUSE	Far Ultraviolet Spectroscopic Explorer
FY	fiscal year
GAIA	Graphical Astronomy and Image Analysis
GALEX	Galaxy Evolution Explorer
GAN	Galactic Neighborhood, Panel on
GBT	Green Bank Telescope
GCT	Galaxies across Cosmic Time, Panel on
GEMS	Gravity and Extreme Magnetism SMEX
GMT	Giant Magellan Telescope
GONG	Global Oscillation Network Group
GRB	gamma-ray burst
GSMT	Giant Segmented Mirror Telescope
HAO	High Altitude Observatory
HAWC	High Altitude Water Čerenkov experiment
HEASARC	High Energy Astrophysics Science Archive Research Center
HEGRA	High Energy Gamma Ray Astronomy
HEPAP	High Energy Physics Advisory Panel
HERA	Hydrogen Epoch of Reionization Array
HESS	High Energy Stereoscopic System
HET	Hobby-Eberly Telescope
HPC	high-performance computing
HST	Hubble Space Telescope
IAU	International Astronomical Union
Inst/Tech	Instrumentation and Technology Development
IPA	Intergovernmental Personnel Act
IPAC	Infrared Processing and Analysis Center
IR	infrared
IRAS	Infrared Astronomy Satellite
IRTF	Infrared Telescope Facility
ISG	Infrastructure Study Group
ISM	interstellar medium

ITAR	International Traffic in Arms Regulations
IXO	International X-Ray Observatory
IYA	International Year of Astronomy
JAXA	Japan Aerospace Exploration Agency
JDEM	Joint Dark Energy Mission
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KPNO	Kitt Peak National Observatory
LBT	Large Binocular Telescope
LDB	Long-duration balloon
LHC	Large Hadron Collider
LIGO	Laser Interferometer Gravitational Wave Observatory
LISA	Laser Interferometer Space Antenna
LMT	Large Millimeter Telescope
LSST	Large Synoptic Survey Telescope
MAGIC	Major Atmospheric Gamma-ray Imaging Čerenkov Telescope
MAST	Multimission Archive at STScI
MIDEX	Medium-scale Explorer
MIE	Model Institutions for Excellence
MoO	Mission of Opportunity
MPS	Mathematical and Physical Sciences, Directorate for (NSF)
MPSAC	Mathematical and Physical Sciences Advisory Committee
MREFC	Major Research Equipment and Facilities Construction
MRI	Major Research Instrumentation
MSP	Math and Science Partnership
NAIC	National Astronomy and Ionosphere Center
NASA	National Aeronautics and Space Administration
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSB	National Science Board
NSF	National Science Foundation
NSF-AGS	National Science Foundation Division of Atmospheric and Geospace Sciences
NSF-AST	National Science Foundation Division of Astronomical Sciences

NSF-OCI	National Science Foundation Office of CyberInfrastructure
NSF-OPP	National Science Foundation Office of Polar Programs
NSF-PHY	National Science Foundation Division of Physics
NSO	National Solar Observatory
NuSTAR	Nuclear Spectroscopic Telescope Array
NVSS	NRAO VLA Sky Survey
OECD	Organisation for Economic Co-operation and Development
OHEP	Office of High Energy Physics (DOE)
OIR	optical and infrared; Optical and Infrared Astronomy from the Ground, Panel on
OSTP	Office of Science and Technology Policy
PAG	Particle Astrophysics and Gravitation, Panel on
PASAG	Particle Astrophysics Scientific Assessment Group
PLATO	Planetary Transits and Oscillations of Stars
PPP	Program Prioritization Panel
PSF	Planetary Systems and Star Formation, Panel on
R&A	research and analysis
R&D	research and development
R&E	research and education
ReSTAR	Renewing Small Telescopes for Astronomical Research
REU	Research Experiences for Undergraduates
RFI	request for information
RMS	radio, millimeter, and submillimeter; Radio, Millimeter, and Submillimeter Astronomy from the Ground, Panel on
RXTE	Rossi X-Ray Timing Explorer
SALT	South African Large Telescope
SDO	Solar Dynamics Observatory
SDSS	Sloan Digital Sky Survey
SETI	Search for Extraterrestrial Intelligence
SFP	Science Frontiers Panel
SIM	Space Interferometry Mission
SKA	Square Kilometer Array
SKA-low	Square Kilometer Array, low-frequency
SMA	Submillimeter Array
SMD	Science Mission Directorate (NASA)
SMEX	Small Explorer
SOAR	Southern Astrophysical Research

SOFIA	Stratospheric Observatory for Infrared Astronomy
SOHO	Solar and Heliospheric Observatory
SPICA	Space Infrared telescope for Cosmology and Astrophysics
SPT	South Pole Telescope
SSB	Space Studies Board
SSE	Stars and Stellar Evolution, Panel on
STC	Science and Technology Center
STEM	science, technology, engineering, and mathematics
STEREO	Solar-Terrestrial Relations Observatory
STScI	Space Telescope Science Institute
Tech/MSP	Technology development and mid-scale projects
TMT	Thirty-Meter Telescope
TRACE	Transition Region and Coronal Explorer
TSIP	Telescope System Instrument Program
UK	United Kingdom
ULDB	ultralong-duration balloon
UNESCO	United Nations Educational, Scientific and Cultural Organization
URO	University Radio Observatory
UV	ultraviolet
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Very Large Array
VLBA	Very Long Baseline Array
VLT	Very Large Telescope
WFIRST	Wide-Field Infrared Survey Telescope
WISE	Wide-Field Infrared Survey Explorer
WIYN	Wisconsin, Indiana, Yale, and NOAO Observatory
WMAP	Wilkinson Microwave Anisotropy Probe
XEUS	X-ray Evolving Universe Spectroscopy
XMM	X-ray Multi-mirror Mission

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