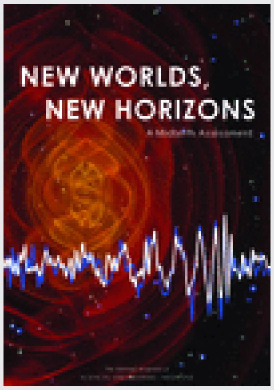

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A Midterm Assessment

Committee on the Review of Progress Toward the Decadal Survey Vision in
New Worlds, New Horizons in Astronomy and Astrophysics

Space Studies Board

Board of Physics and Astronomy

Division on Engineering and Physical Sciences

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Preface

The Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics was charged to review the responses of NASA's Astrophysics program, the National Science Foundation's (NSF's) Astronomy program, and the Department of Energy's (DOE's) Cosmic Frontiers program (hereafter the agencies' programs) to previous National Research Council (NRC)[1] advice, primarily the 2010 decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*[2] (hereafter referred to as NWNH). The complete statement of task is reprinted in Appendix A.

To address its task, the committee held four in-person meetings, including a science symposium, and many teleconferences during its work from October 2015 through May 2016. These meetings involved speaking with government policymakers, researchers in the community, authors of earlier advisory reports (including those of the NRC), the leaders of ongoing activities recommended in NWNH, and foreign space agency representatives. In particular, the science symposium, held on December 12, 2015, at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, California, featured leading astronomers who provided assessments of the scientific progress in each of the Science Frontier Panel areas of the 2010 astronomy and astrophysics decadal survey.[3] The committee also organized a splinter meeting at the January 2016 meeting of the American Astronomical Society in Kissimmee, Florida, at which the committee provided a brief summary of its scope and activities and then engaged in discussion with the attendees. Lastly, the committee created a public email box for anyone who wished to provide input to the study process.

This report was written to convey the substantial and exciting progress that has been achieved in astronomy and astrophysics since the August 2010 release of NWNH, to describe the events and factors that have constrained further discovery, and to recommend actions that could give humankind an even deeper understanding of our universe.

The committee discussed its scope extensively. As stated in its task, the committee is not to "revisit or alter the scientific priorities or mission recommendations" from NWNH or other reports of the NRC, but could "provide guidance on implementation of the recommended science and activities portfolio and on other potential activities in preparation for the next decadal survey." This guidance therefore prohibited the committee from changing the survey's priorities but did provide the latitude to recommend course corrections, where needed, as long as the relative priorities of the survey were maintained.

A general priority of NWNH was restoring and then maintaining a balanced astronomy and astrophysics portfolio. Likewise, echoing NWNH's perspective, the current committee similarly stressed the importance of executing a balanced research program. Thus, in the section "The Goal of a Balanced Program," in Chapter 2 of this report, the committee lays out the guiding principles on balance taken from NWNH and used in its analysis of the present science program. This layout of this report mirrors the

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the NRC are used in an historical context identifying programs prior to July 1.

[2] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[3] These panels' scientific areas were Cosmology and Fundamental Physics, the Galactic Neighborhood, Galaxies across Cosmic Time, Planetary Systems and Star Formation, and Stars and Stellar Evolution.

committee's charge. Chapters 1 and 2 describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in astronomy and astrophysics over the years since the publication of NWNH. Chapters 3 and 4 assess how well the agencies' programs address the strategies, goals, and priorities outlined in NWNH and other relevant NRC reports; assess the progress toward realizing these strategies, goals, and priorities; and recommend actions that could be taken to maximize the science return of the agencies' programs. Concluding the report, Chapter 5 responds to the element of the committee's task to provide guidance on potential activities in preparation for the next decadal survey.

For consistency with NWNH and per its charge, the committee incorporated the scientific scope of NWNH into its own assessment. Per the survey, "[o]nly 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. Direct detection of dark matter was also excluded from prioritization." NWNH also excluded ground-based observations of gravitational waves, so the committee did as well.

The committee was fortunate enough to be able to rely on recent work done by other committees, including *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*,[4] *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*,[5] *The Space Science Decadal Surveys: Lessons Learned and Best Practices*,[6] and annual reports of the Astronomy and Astrophysics Advisory Committee, among others. These reports provided the current committee with an indispensable source of background and analysis on many complex topics that it did not have the time nor depth of knowledge in which to be able to delve effectively.

On behalf of the committee, I would like to thank the many very busy people in the U.S. government and astronomy and astrophysics community, as well as those abroad, who helped the committee through presentations, written input, and discussions. A special thanks goes to the staff of the Board on Physics and Astronomy and the Space Studies Board: Katie Daud, James Lancaster, David Lang, Michael Moloney, Linda Walker, and Dionna Williams. Their guidance and support were critical to the success of this effort. This report, although ultimately written by the committee, was only possible thanks to the countless pieces of input contributed by many.

Jacqueline N. Hewitt, *Chair*
Committee on the Review of Progress Toward the
Decadal Survey Vision in New Worlds, New Horizons
in Astronomy and Astrophysics

[4] NRC, 2014, *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[5] NRC, 2015, *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*, The National Academies Press, Washington, D.C.

[6] National Academies of Sciences, Engineering, and Medicine, 2015, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. 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:

Eric G. Adelberger, University of Washington,
Steven J. Battel, Battel Engineering,
Mitchell Begeleman, University of Colorado, Boulder,
James Fienup, University of Rochester,
B. Scott Gaudi, The Ohio State University,
Lynne Hillenbrand, California Institute of Technology,
Robert P. Kirshner, Gordon and Betty Moore Foundation,
Rene Ong, University of California, Los Angeles,
George H. Rieke, University of Arizona,
Adam G. Riess, Johns Hopkins University, and
Anneila Sargent, California Institute of Technology.

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, who was 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

Summary

New Worlds, New Horizons in Astronomy and Astrophysics[1] (NWNH), the report of the 2010 decadal survey of astronomy and astrophysics, put forward a vision for a decade of transformative exploration at the frontiers of astrophysics. This vision included mapping the first stars and galaxies as they emerge from the collapse of dark matter and cold clumps of hydrogen, finding new worlds in a startlingly diverse population of extrasolar planets, and exploiting the vastness and extreme conditions of the universe to reveal new information about the fundamental laws of nature. NWNH outlined a compelling program for understanding the cosmic order and for opening new fields of inquiry through the discovery areas of gravitational waves, time-domain astronomy, and habitable planets. Many of these discoveries are likely to be enabled by cyber-discovery and the power of mathematics, physics, and imagination. To help realize this vision, NWNH recommended a suite of innovative and powerful facilities, along with balanced, strong support for the scientific community engaged in theory, data analysis, technology development, and measurements with existing and new instrumentation. Already in the first half of the decade, scientists and teams of scientists working with these cutting-edge instruments and with new capabilities in data collection and analysis have made spectacular discoveries that advance the NWNH vision. This summary begins by presenting highlights at mid-decade of this remarkable scientific progress. The full report describes these key results in more detail, as well as a broad palette of other similarly exciting advancements in astronomy and astrophysics from the first half of this decade.

Following more than two decades of pioneering investment by the National Science Foundation (NSF) in high-risk, high-payoff technologies for precision measurement, the Advanced Laser Interferometry Gravitational-wave Observatory (LIGO) detected gravitational waves emitted by two distant black holes that collided and merged 1.3 billion years ago. This first direct detection of gravitational waves confirms Einstein's prediction that gravitational waves exist and that they transport energy through a dynamic spacetime. The waveforms are consistent with general relativity and encode information about the warping of space and time near the event horizons of the black holes. The direct detection of gravitational waves enables new, stringent tests of general relativity and, as envisioned by NWNH, initiates the discovery area of gravitational wave astronomy for studying the most extreme events in the universe across cosmological distances.

The Kepler satellite has enabled the discovery of an extraordinary diversity of planets and planetary systems, and through a careful census of the demographics of these planets, we have learned that there must be billions of Earth-sized worlds throughout our galaxy. Determining the nature of these many planets is extremely challenging, but the combination of transit measurements and high-precision ground-based Doppler studies has identified seven that are similar in size and density to Earth. A ground-based survey has recently discovered an Earth-sized planet only 39 light years distant. The technology of coronagraphy has advanced, and it has already resulted in the direct images of massive planets around younger stars.

With the deepest surveys from the Hubble Space Telescope (HST), astronomers have discovered hundreds of galaxies from the first billion years of cosmic history, and radio experiments are approaching the whisper-like sensitivity needed to detect the primeval transition when ionization of hydrogen made the universe transparent to ultraviolet light. With these observations, scientists are beginning to probe the

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

Cosmic Dawn of stars and galaxies. The combination of mid-infrared photometry from Spitzer and observations from HST has allowed identification of the very highest redshift galaxies whose emissions have shifted into the infrared wavelength range.

An important milestone was reached in 2015 with the completion of the Atacama Large Millimeter/submillimeter Array (ALMA). ALMA has already enabled transformational results on planet formation in the observations of HL Tau and TW Hya, and has opened new windows on the study of the mass loss in evolved stars. ALMA has also yielded direct kinematic measurements of the masses of supermassive black holes in nearby galaxies, with a precision better than HST, among other major advances.

FINDING 2-4: The completion and successful operation of ALMA are a remarkable success and the culmination of significant investment by NSF through the Major Research Equipment and Facilities Construction (MREFC) program.

Similarly, the Daniel K. Inouye Solar Telescope (DKIST) has been fully funded by the MREFC program, and the community anticipates operation beginning in 2019, launching unprecedented capabilities for studying variability and magnetic phenomena in the Sun, with broad implications for plasma processes that underlie a wide variety of astrophysical phenomena throughout the universe.

The James Webb Space Telescope (JWST) is scheduled for launch in late 2018, now on track following a rebaselining in 2011, and it is expected to deliver the groundbreaking scientific capability that was envisioned when it received the highest ranking in the 2001 decadal survey.[2] Its superb near-infrared sensitivity and angular resolution will allow detailed characterization of redshift z = 8-12 galaxies that are barely detectable with HST, as well as enable the discovery of the smallest of the universe's first galaxies below the sensitivity limits of current telescopes. JWST will study in unprecedented detail the birth of stars and protoplanetary disks; may detect individual supernovae occurring in the first galaxies; will provide a huge leap in sensitivity for studies of relatively cool planets, including many targets identified by the Transiting Exoplanet Survey Satellite (TESS); and will provide radically new insights into the composition and structure of exoplanet atmospheres.

The above assessment of spectacular scientific productivity and progress in new instrumentation during the first half of the decade has to be tempered, however, by acknowledgment of budget realities and programmatic developments and the resultant limited progress toward the full program envisioned by NWNH.[3]

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

[3] The survey provided some discussion of the priorities in scenarios in which less funding was available than was planned for. For NASA:

> 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 . . . to start LISA as soon as possible subject to . . . conditions . . . and to invest in IXO technology development . . . . The third priority is to pursue the CMB Technology Development Program . . . .

For NSF:

> 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.

> (See NRC 2010, *New Worlds, New Horizons*.)

FINDING 2-1: The NSF-AST budget through the first half of the decade has been approximately flat in real-year dollars. This budget reality is somewhat lower than that baselined by NSF for NWNH (approximately flat in inflation-adjusted dollars) and significantly lower than that assumed by NWNH (doubling in real-year dollars).

FINDING 2-2: For NASA-APD, NWNH assumed a flat budget in inflation-adjusted dollars. The actual combined budget for NASA-APD and JWST has roughly tracked this assumption. However, the late-breaking schedule delay and associated budget increase of JWST have delayed the availability of funding for new initiatives by about 4 to 5 years.

FINDING 2-3: At the Department of Energy (DOE), support for astrophysics has been strong, and the budget reality has been close to the baseline plan presented in NWNH.

NWNH advocated a program of vigorous investment in research, new facilities, and human infrastructure. The highest-priority, new, large-scale ground-based facility—the Large Synoptic Survey Telescope (LSST)—is well along the path envisioned by NWNH for exploiting new technologies to address the most important astrophysics questions. LSST was awarded NSF MREFC funding in 2014 and, in combination with DOE construction of its 3.2-gigapixel camera, it is on schedule for first light in 2020 and a 10-year science survey commencing in 2022. LSST will survey the entire sky visible from its site in Chile more than 800 times in six colors. It will produce unprecedented catalogs of objects and of variable and transient events, exploring the NWNH discovery frontier of time-domain astronomy.

FINDING 3-1: LSST planning and construction have progressed well and are on schedule and within budget, successfully bringing together NSF funding, DOE funding, and private funding.

FINDING 3-2: Current projections for LSST performance and data products promise transformational scientific impact, as envisioned by NWNH. To realize the full scientific potential of this great new facility, funding that enables individual investigators and groups of investigators to deliver the scientific results will be critical.

The second-highest priority for the ground-based program, the Mid-Scale Innovations Program (MSIP), is a competed program intended to fund projects and activities that fall between the funding boundaries of the NSF Major Research Instrumentation program and the MREFC program. Midscale facilities had been funded in the past by NSF, but in an ad hoc manner, and NWNH recommended a program that would enable these activities to be regularly competed at an increased level of funding. NSF-AST created a funding stream for MSIP by combining several existing programs, including its previously unsolicited midscale program, the university radio observatories, and the optical telescope instrumentation program. With these funds, MSIP has supported an exciting set of highly ranked proposals in a heavily oversubscribed competition. The inability to fund the program at the level envisioned by NWNH, however, represents a significant loss of scientific opportunity.

FINDING 3-3: Implementation of the NWNH recommendation of MSIP has been possible only by subsuming previous programs into MSIP and by aggressive divestment from older facilities. The total NSF-AST funding for mid-scale initiatives has dropped by nearly a factor of two since the start of the decade, in stark contrast to the NWNH recommendation of MSIP as a new initiative which would expand opportunities for mid-scale projects.

FINDING 3-4: Despite limited resources for MSIP, NSF-AST has funded an exciting set of highly ranked proposals in a heavily oversubscribed competition. Some mid-scale programs recommended by NWNH have also moved forward with funding from DOE and from the

NSF Physics and Polar Programs. The scientific promise of these projects confirms the NWNH expectation that a mid-scale program would enable major advances that respond nimbly to opportunities on a diverse range of science topics.

Participation in one of the U.S. Giant Segmented Mirror Telescope (GSMT) projects was the third-ranked large priority in ground-based astronomy. The highly constrained budget environment has prevented any significant involvement by NSF-AST in either of the two GSMT projects so far this decade. Both projects are proceeding with private funding and with support from international partners. Site preparation and initial construction activities have begun for the two projects, and both are working to engage the broader U.S. science community.

FINDING 3-5: The Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT) projects have both made major progress since 2010, and both offer technically feasible routes to achieving the GSMT science goals set forth by NWNH. However, programmatic hurdles remain, and neither project has secured the funding needed to complete construction at its full intended scope. NSF budget constraints have prevented NSF's implementation of the NWNH recommendation that NSF-AST select one partner and participate in GSMT construction.

An Atmospheric Cerenkov Telescope Array (ACTA) was ranked fourth in the ground-based, large-scale projects in NWNH. The leading ground-based teams in this field worldwide have joined to form the Cerenkov Telescope Array (now CTA). With support from NSF, progress has been made in technology development addressing new telescope concepts and in maturing the array design. If sufficient funding is secured, construction could proceed as early as 2016. The U.S. groups have developed a plan for participation in CTA, but at a lower level than that originally proposed at the time of NWNH.

FINDING 3-7: U.S. participation in CTA at budget levels below those recommended by NWNH would still have a significant positive impact on the scientific productivity of the observatory and would give U.S. scientists leadership roles in the CTA program. If the U.S. CTA proposal competes successfully in the MSIP and NSF-Physics mid-scale programs, the NWNH recommendation can be implemented, albeit at a level lower than anticipated in 2010.

NWNH had a single recommendation for a medium-scale, ground-based facility, the Cerro Chajnantor Atacama Telescope (CCAT, formerly the Cornell-Caltech Atacama Telescope), a submillimeter-wave survey telescope. The NSF Portfolio Review placed funding for MSIP at a higher priority than funding for the construction of CCAT. As a result, NSF-AST did not provide directed funding for CCAT. The CCAT consortium subsequently submitted a proposal to the MSIP competition, but this proposal was not funded. In the current budget climate, NSF will only contribute to CCAT through future MSIP competitions. The project is now being rebaselined, and a number of potential international partners have expressed interest, including the host country of Chile.

FINDING 3-8: In the current budget climate, NSF-AST has not been able to fund CCAT beyond an initial contribution to the design. This is because the NSF-AST budget increases anticipated by NWNH did not materialize, and NSF-AST, consistent with the Portfolio Review's guidance, gave higher priority to funding the MSIP program within the constraints imposed by the budget.

While NWNH placed strong emphasis on expanding support for individual investigator grants, the core grants programs have declined in real-year dollars and dropped still further in purchasing power over the first half of the decade, following the trends of the overall NSF-AST budget. This reduction in funding has contributed to a substantial decline in grant funding rates, significantly impacting the scientific productivity of the community. NWNH also specifically recommended a number of small-scale activities for enhancing the scientific productivity of the ground-based astronomy program. One of these activities, augmented U.S. access to Gemini, occurred at no cost to NSF because the United Kingdom withdrew from the partnership. With the exceptions of the augmentation of U.S. participation in Gemini and 2 years of funding for Theory and Computation Networks, NSF-AST has been unable to achieve any of these recommendations, and all of these programs are now funded at a lower level than they were in 2011.

FINDING 3-9: Because the NSF-AST budget did not grow as assumed by NWNH, NSF-AST has not implemented the majority of the NWNH recommendations for small-scale projects or for expanded support for individual investigator programs. Support for the individual investigator programs has decreased during the first half of the decade.

The shrinking of small- and mid-scale investment at NSF is symptomatic of a more general problem: in a flat NSF-AST budget, the operations costs of powerful new facilities are squeezing out funding for mid-scale and individual investigator programs. Recognizing the need to divest from older facilities to release funds for new ones, NWNH recommended that NSF conduct a senior review of all its existing facilities. NSF-AST responded with a full Portfolio Review and, thereby, received advice from the community on the prioritization of the existing facilities in the context of its overall program. NSF-AST is in the process of implementing a vigorous divestment program. However, divestment is a challenge, and even with the recommended divestment, the projected NSF-AST budgets are not sufficient to fund both the operations of the upcoming new facilities and their research programs.

The expected operations costs for ALMA, DKIST, and LSST by the beginning of the next decade will, in the presence of a flat NSF-AST budget, severely constrict the already squeezed mid-scale, small, and individual investigator programs and limit the community's ability to sustain a robust ground-based astronomy and astrophysics program. The remarkable scientific progress of the first half of the decade was made possible by capital investment in previous decades. Without funding for a balanced program that realizes the benefits of this decade's capital investment, the visionary scientific program put forward by NWNH will not be realized.

FINDING 3-12: Even following the divestment recommended by the Portfolio Review, the operations costs of ALMA, DKIST, and LSST will compromise the ability of the U.S. community to reap the scientific return from its premier ground-based facilities. Moderate increases in the NSF-AST budget would have highly leveraged science impact as a consequence of these powerful new facilities.

RECOMMENDATION 3-1: The NSF should proceed with divestment from ground-based facilities that have a lower scientific impact, implementing the recommendations of the NSF Portfolio Review, which is essential to sustaining the scientific vitality of the U.S. ground-based astronomy program as new facilities come into operation.

RECOMMENDATION 3-2: The NSF and the National Science Board should consider actions that would preserve the ability of the astronomical community to fully exploit the Foundation's capital investments in ALMA, DKIST, LSST, and other facilities. Without such action, the community will be unable to do so because at current budget levels the anticipated facilities operations costs are not consistent with the program balance that ensures scientific productivity.

The Wide-Field Infrared Survey Telescope (WFIRST) was NWNH's highest-ranked large space initiative, with a science program that incorporated precision measurements of cosmic acceleration from large imaging, spectroscopic, and supernova monitoring surveys; statistical characterization of the demographics of exoplanet systems from a gravitational microlensing survey of the galactic bulge; a large area survey of the galactic plane; and a wide range of galactic and extragalactic investigations enabled by guest investigator studies of the survey data sets and by a Guest Observer (GO) program. Substantial progress has been made in the first half of the decade toward realizing WFIRST, although its scope, design, and launch date have changed since the original concept put forward by NWNH. Anticipating the successful completion of JWST, WFIRST entered Phase A in FY2016 and is moving toward launch in 2025. While the formal mission start was delayed 3 years beyond NWNH's anticipated start in 2013 and 5 years beyond NWNH's anticipated launch in 2020 as a result of the delayed completion of JWST, the extended pre-formulation phase allowed substantial technology development, most importantly the adoption of larger-format infrared detectors and the 2.4-meter telescope assembly that became available in 2012. A vigorous program in coronagraphy technology development, coupled with the 2.4-meter telescope assets, has extended WFIRST's capabilities in the study of exoplanets to include the exciting prospect of direct detection of large planets orbiting nearby stars.

FINDING 4-1: The 2.4-meter telescope, larger infrared detectors, and addition of a coronagraph make the 2016 design of WFIRST an ambitious and powerful facility that will significantly advance the scientific program envisioned by NWNH, from the atmospheres of planets around nearby stars to the physics of the accelerating universe.

The WFIRST coronagraph responds to an opportunity that arose after NWNH—the availability of a 2.4-meter telescope, which enables a space-borne coronagraph to carry out an exciting exoplanet science program. It also demonstrates technology needed for future missions capable of imaging Earth-like planets around nearby stars and is therefore responsive to the NWNH recommendation of a New Worlds Technology Development Program. Given the remarkable developments in exoplanet discovery and the emphasis on this science area in NWNH, the committee agrees that the addition of the coronagraph represents an appropriate shift in emphasis for WFIRST's science program. However, some of the wide-field survey capabilities envisioned by NWNH have been deemphasized and, as noted by *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*,[4] with the larger mirror and the coronagraph, the risk for cost growth of the mission is now greater.

FINDING 4-5: Coronagraph technology has matured rapidly over the past 2 years, addressing one of the key recommendations of the 2014 report *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*. The coronagraph remains a schedule, cost, and technical risk for WFIRST.

An independent estimate of the 2015 WFIRST Design Reference Mission projected its cost at $2.3 billion to $2.5 billion (FY2015 dollars) and found that the cost growth since the NWNH estimate was fully attributable to the coronagraph, the GO program, and inflation. However, changes in the mission design leading up to Key Decision Point A led to an increase in the estimated mission cost of approximately 25 percent ($550 million).

FINDING 4-2: Because of the risk of cost growth, the concern raised in *Evaluation of the Implementation of WFIRST/AFTA* that WFIRST could distort the NASA program balance remains a concern. In addition, the delay in the implementation of WFIRST over the

[4] NRC, 2014, *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

schedule anticipated in NWNH means that cost growth in WFIRST would limit options for the next decadal survey.

RECOMMENDATION 4-1: Prior to Key Decision Point B, NASA should commission an independent technical, management, and cost assessment of the Wide-Field Infrared Survey Telescope, including a quantitative assessment of the incremental cost of the coronagraph. If the mission cost estimate exceeds the point at which executing the mission would compromise the scientific priorities and the balanced astrophysics program recommended by the 2010 report *New Worlds, New Horizons in Astronomy and Astrophysics*, then NASA should descope the mission to restore the scientific priorities and program balance by reducing the mission cost.

NASA's Explorer program has a distinguished history of high scientific impact through the deployment of relatively low-cost missions that can respond to opportunities on a short timescale. The Explorer missions also provide a strong connection between NASA and the university community, with benefits to intellectual cross-fertilization and the training of students and future mission Principal Investigators. NWNH recommended a significant augmentation of the Explorer program—doubling, or more than doubling, the number of mission selections per decade. Like the mid-scale program at NSF, limited budgets have had a very large impact on NASA's Explorer program. The first Announcement of Opportunity for a Mission of Opportunity (MoO) was canceled before selection. The second round, including calls for both a Smaller Explorer (SMEX) and an MoO, has so far enabled three SMEX and two MoO Phase A studies to begin. The NASA-APD plan includes a total of four opportunities and selections of Explorers, each with an MoO, during this decade. The committee is concerned that growth in NASA-APD's large programs may prevent even this reduced implementation of the Explorer program augmentation. Maintaining the budget profile is critical for this important program to succeed as envisioned by NWNH.

RECOMMENDATION 4-3: NASA's Astrophysics Division should execute its current plan, as presented to the committee, of at least four Explorer Announcements of Opportunity during the 2012-2021 decade, each with a Mission of Opportunity call, and each followed by mission selection.

NASA-APD's intent to execute four Explorer opportunities this decade, despite budgetary constraints, is commendable. If budgets increase, restoring the full Explorer augmentation would be consistent with the priorities of NWNH.

The third-ranked large-class space mission recommended in NWNH was the Laser Interferometer Space Antenna (LISA). Because of JWST's cost increase and LISA's ranking, it became clear early in the decade that NASA would not have the resources to begin a gravitational wave space mission in the 2010s. This led to the European Space Agency's (ESA's) decision to proceed without U.S. involvement, which in turn led to the loss of science and technology funding directed toward the mission in the United States. The ESA-led LISA Pathfinder (LPF), a mission intended to demonstrate certain technologies needed by a space-based gravitational wave detector, was launched in December 2015, several years behind schedule. NWNH's ranking of LISA was based on the expectation of an equal ESA-NASA partnership, and NWNH identified a decision point based on the outcome of LPF that would trigger a mid-decade assessment of whether to proceed with LISA.

The dramatic direct detection of gravitational waves by LIGO greatly strengthens the scientific case for a space-based mission by establishing gravitational wave astronomy as a revolutionary new probe of astrophysical phenomena. LISA would explore the source-rich millihertz band that is inaccessible from the ground, allowing for the detection of massive galactic black holes and intermediate-mass black holes throughout the universe, and providing unique insight into early black hole–galaxy coevolution. Relative to LIGO, typical LISA detections would have higher signal-to-noise ratios and execute many more cycles in band, allowing for more precise measurements and significantly stronger tests of general relativity. The early operation of LPF has been successful, and its results have demonstrated the feasibility of many of the key technologies needed by LISA.[5] The committee believes that NASA and ESA together should rethink their strategy for LISA and take steps to reduce mission risk and to maximize its scientific return as recommended below.

RECOMMENDATION 4-4: NASA should restore support this decade for gravitational wave research that enables the U.S. community to be a strong technical and scientific partner in the European Space Agency (ESA)-led L3 mission, consistent with the Laser Interferometer Space Antenna's high priority in the 2010 report *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH). One goal of U.S. participation should be the restoration of the full scientific capability of the mission as envisioned by NWNH.

The fourth-priority large-scale mission in NWNH was the International X-ray Observatory (IXO). Recognizing that it was unlikely that IXO could proceed in the 2010s, NWNH recommended a substantial technology development program in preparation for the next decade. However, if IXO were selected as ESA's first large mission, then NWNH recommended that NASA accelerate the program with guidance from the community. Because of the budget constraints early in this decade in the United States, ESA is instead proceeding with Athena, an ESA-led X-ray mission that is reduced in scope but whose capabilities address many of the science goals of IXO, as its second large mission. The committee acknowledges that Athena enables a compelling subset of the science envisioned for IXO and that participation in Athena therefore addresses the high priority given to IXO science by NWNH.

RECOMMENDATION 4-5: NASA should proceed with its current plan to participate in Athena, with primary contributions directed toward enhancing the scientific capabilities of the mission.

In the category of space-based, medium-scale activities, NWNH recommended two technology development programs, the New Worlds Technology Development (NWTD) Program and an Inflation Probe Technology Development (IPTD) Program. Advancing the technology of starlight suppression was an important goal of NWTD, along with exploring options for a future mission for studying habitable exoplanets. NWNH recommended a mid-decade review and selection of appropriate starlight suppression technology for full development. Events played out differently than anticipated, and the WFIRST coronagraph is the main activity aimed at NWTD, satisfying some aspects of the broader program envisioned by NWNH. The WFIRST coronagraph, combined with other smaller programs still supported by NASA-APD, represents a decadal investment larger than that envisioned by NWNH. The committee believes that this is an appropriate response to the rapid advancements in exoplanet science but reiterates that WFIRST cost growth and its effect on scientific prioritization and program balance is a major concern.

Measuring the B-modes of the cosmic microwave background (CMB) polarization caused by gravitational waves created during inflation is the major long-term goal of IPTD, as well as neutrino mass, mapping large-scale structure with gravitational lensing, and reionization science. Measurements by Planck, ground-based instruments, and balloon-borne instruments continue to improve and to place increasingly stringent limits on the amplitude of the B-modes and therefore on the energy scale associated with inflation. Enormous progress has been made in the capabilities of detector systems and other technologies needed for improved sensitivity of polarization measurements. The CMB community has

[5] M. Armano, H. Audley, G. Auger, J.T. Baird, M. Bassan, P. Binetruy, M. Born, et al., 2016, Sub-femto-g free fall for space-based gravitational wave observatories: LISA pathfinder results, American Physical Society Physical Review Letters 116(23):231101-1-231101-10.

recently defined a program, CMB-S4, to identify science goals and instrument requirements for the next generation of experiments, with potential support from NASA, NSF, and DOE. These activities are well aligned with the NWNH recommendation for IPTD, with all three agencies supporting technology development and precursor science on a path to a future space mission.

As for the ground-based program, NWNH recommended a slate of small space-based projects and activities, consistent with its emphasis on program balance. Despite the challenging budget environment, NASA has roughly maintained the funding level of its core and research programs, although the committee notes that this was preceded by a decline in overall funding for individual investigator grants at the end of the past decade. The greatest challenge to the maintenance of program balance is NASA-APD's investment in its large missions, JWST and WFIRST, and the risk of growth in their cost.

1

Scientific Discoveries and Technical Advances

The 2010 astronomy and astrophysics decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH), organized its discussion of the decadal science program around the themes of Cosmic Dawn, New Worlds, Physics of the Universe, and The Larger Science Program. This summary of scientific discoveries since NWNH is organized in the same categories. The committee emphasizes, as did NWNH, that these themes capture only some of the highlights of an extraordinarily rich palette of astronomical discovery that ranges from our own solar system to the edge of the observable universe, and from the first instants of cosmic time to the present day.

COSMIC DAWN: SEARCHING FOR THE FIRST STARS, GALAXIES, AND BLACK HOLES

On the theme of cosmic dawn, the most important advances in the first half of the decade have come from large surveys of the high-redshift universe with the Hubble Space Telescope (HST), often exploiting the near-infrared and grism capabilities of the Wide Field Camera 3 (WFC3) installed as part of the 2009 Hubble servicing mission. These surveys, augmented by space- and ground-based observations at other wavelengths, have dramatically improved understanding of galaxy populations in the first billion years of cosmic history. At redshifts $z = 6$-8, the field has advanced with astonishing speed from the first tentative detections to reliable measurements of luminosity functions that span a factor of 100 or more in galactic star formation rate. The new frontier of discovery is at redshifts $z = 9$-12, within 500 million years of the Big Bang. Galaxies in this era are being found both in large area surveys and in projects like the CLASH Treasury Program and the Hubble Frontier Fields, which use clusters of galaxies as gravitational telescopes to bring small patches of the distant universe into magnified view (Figure 1.1). Star-forming galaxies grow steadily in number from $z = 10$ to $z = 6$, roughly tracking the theoretically predicted growth of their parent halos of dark matter. Hydrogen Lyman-α emission from these early galaxies appears to decline rapidly at $z > 6$, which suggests that the Lyman-α photons at early epochs are being absorbed by a blanket of intervening neutral hydrogen. Hydrogen absorption spectra of quasars and gamma-ray bursts at $z > 6$ also suggest that the transparency of the intergalactic medium is changing rapidly at this epoch. Extragalactic observations with Atacama Large Millimeter Array (ALMA) are beginning to indicate the potential of ALMA spectroscopy at high redshift.

Cosmic microwave background (CMB) observations from the Planck satellite now suggest that intergalactic hydrogen was mostly reionized by $z \approx 7$, somewhat later than previous estimates from the Wilkinson Microwave Anisotropy Probe (WMAP). With plausible extrapolations in luminosity and redshift, ultraviolet photons from the observed population of high-redshift galaxies appear sufficient to achieve reionization by this epoch. However, the relative contributions of bright and faint galaxies, and the potential contribution of X-rays and ultraviolet photons from accreting black holes, remain matters of debate. A powerful way to address these questions is to directly map redshifted 21 cm emission and

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

absorption by neutral hydrogen throughout the epoch of reionization. Specially designed radio experiments are now approaching the sensitivity thought needed to detect the predicted signals, and they have demonstrated the ability to remove contamination from astrophysical and terrestrial foregrounds, which present the most challenging technical obstacle to mapping reionization. Cosmological simulations and semi-analytic models, incorporating gravitational clustering, hydrodynamics, star formation, and radiative transfer, play a crucial role in connecting observed galaxy counts to the physical mechanisms of reionization and in making predictions for the complex structures expected in 21 cm maps.

FIGURE 1.1 The Hubble Frontier Fields image of the galaxy cluster MACS J07175+3745. Faint blue arcs are distant galaxies that have been magnified and distorted by the light-bending gravity of the massive cluster in front of them. The six clusters observed to unprecedented depth by the Frontier Fields program serve as natural gravitational telescopes, allowing Hubble to discover galaxies back into the first half billion years of cosmic history. SOURCE: Courtesy of NASA, ESA and the HST Frontier Fields team (STScI).

The next 5 years should see major further advances in the study of the cosmic dawn. Observing the first stars and galaxies is a defining objective of JWST, and its superb near-infrared sensitivity and angular resolution will allow detailed characterization of z = 8-12 galaxies that are barely detectable with HST, as well as detection of galaxies down to the limiting mass imposed by the physics of atomic gas cooling in dark matter halos. JWST may also detect individual supernovae arising in galaxies at these redshifts, and even earlier.

In the longer run, the Wide-Field Infrared Survey Telescope (WFIRST) will execute imaging surveys that equal the deepest HST observations over areas hundreds or thousands of times larger; both WFIRST and Athena will help to assess the relative contribution of galaxies and active galactic nuclei to reionization. CMB polarization experiments will provide sharper constraints on the timing and duration of the epoch of reionization. Building on the current generation of radio experiments, the Hydrogen Epoch of Reionization Array (HERA) project is proceeding with initial funding from the National Science Foundation's (NSF's) Mid-Scale Innovations Program (MSIP). With further development, HERA and its successors will map the large scale structure of the young universe and trace the process by which the first galaxies filled it with ultraviolet light.

NEW WORLDS: SEEKING NEARBY, HABITABLE PLANETS

Since 2010, the number of detected exoplanets has grown from under 1,000 to more than 5,000, with the majority of new systems coming from NASA's Kepler mission. But numbers alone understate Kepler's impact: by opening new windows of parameter space, it has discovered a diversity of planets and planetary systems far beyond that previously known. Transit measurements of planet diameters, especially when combined with mass measurements from radial velocity follow-up or from transit timing variations, provide critical diagnostics of exoplanet compositions. Kepler discoveries range from dense, iron-rich planets like Mercury to planets of solid rock or molten lava, to water worlds and ice giants and gas giants puffier than Jupiter and Saturn. "Super-Earths," intermediate in size between Earth and Neptune, have been found in great abundance, commonly in compact and flat systems of multiple planets in nearly circular orbits. The most tightly packed Kepler systems have four or five planets, all with orbital radii smaller than Mercury's. Other systems have planets orbiting binary stars, natural realizations of the science-fiction vision of a world with two suns. Small planets are an order of magnitude more abundant than giant planets, confirming a generic prediction of the core accretion theory of planet formation. Sun-like stars have an average of about one planet larger than Earth with an orbital period shorter than a year, and Kepler's census implies billions of Earth-like worlds in the Milky Way.

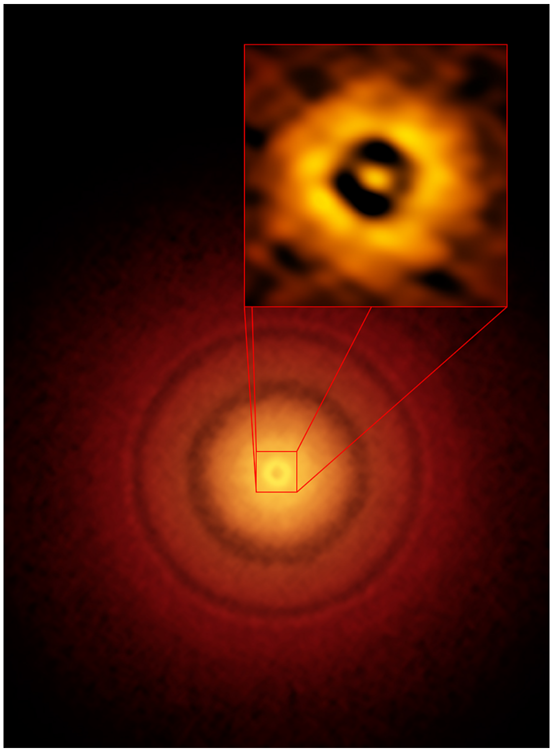

FIGURE 1.2 Atacama Large Millimeter Array (ALMA) image of the planet-forming disk around the young, Sun-like star TW Hydrae. The inset image (upper right) zooms in on the gap nearest to the star, which is at the same distance as Earth is from the Sun, suggesting an infant version of our home planet could be emerging from the dust and gas. The additional concentric light and dark features represent other planet-forming regions farther out in the disk. SOURCE: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO).

Ground-based transit, radial velocity, microlensing, and direct imaging searches have also made great strides over the decade. Transit observations show that some hot Jupiters are inflated because of proximity to their parent stars, and roughly half of them have orbits misaligned with their parent star's spin, which suggests emplacement by dynamical scattering rather than slow migration or in situ formation. High-precision radial velocity surveys can now measure stars moving at the speed of a slow walk, and some searches are now targeting cooler stars for which rocky planets in the habitable zone would produce a detectable signal. Several strong candidates for such potentially habitable worlds are now known. Microlensing is most sensitive to planets with orbital radii of several astronomical units, and the technique has so far discovered roughly 50 planets in 44 systems, showing that there is, on average, roughly one planet per star beyond the snow line (where ices can form in a protoplanetary disk) with mass between 5 M_{Earth} and 10 $M_{Jupiter}$. The ongoing Spitzer Space Telescope mission has been highly successful for the characterization of transiting extrasolar planets, particularly as the primary source of measurements of thermal emission from secondary eclipses. Coronagraphic instruments that exploit adaptive optics on 8-meter telescopes are yielding direct images of massive planets around younger stars, probing the boundaries between planets and brown dwarfs, and between star formation and planet formation.

The disks of gas and dust around forming stars are the nurseries where planets and planetary systems are born. Images of protoplanetary and transitional disks at a range of wavelengths reveal detailed structures that trace the process of star and planet formation. In scattered light observations at infrared wavelengths, proto-stars with infalling dusty envelopes and obscured mid-planes are visible within large molecular clouds. The expected transformational power of ALMA at millimeter wavelengths is apparent in early observations of disks that probe rotational dynamics, fine spatial structure, and chemical composition. Most spectacularly, the disk of proto-star TW Hydrae is deeply sculpted with rings and gaps, possibly caused by orbiting planets (Figure 1.2). Other ALMA observations confirm the predicted disappearance of molecular gas species at the large separations where they freeze into solid particles. Disk observations with extreme adaptive optics systems reveal streams and spiral arms, whose structure may be related to the masses of embedded planets. High-resolution images of the young system LkCa15 show an annulus of cold dust and gas with an object that may be an accreting planet orbiting within its inner gap.

Progress should come on many fronts in the next 5 years. Compared to the Kepler prime mission, the continuing "K2" campaigns will target a greater number of stars with a greater range of properties and galactic environments, albeit with less sensitivity to small planets or long orbital periods. Because it is targeting a larger area, K2 is also finding planets around brighter stars than those in the primary mission. The Transiting Exoplanet Survey Satellite (TESS), scheduled for launch in December 2017, will use similar techniques to Kepler but will observe bright, relatively nearby stars over the whole sky, thus identifying targets that are ideal for radial velocity mass determinations and transit spectroscopy. A new generation of microlensing surveys will greatly expand the census of low-mass planets at distances near and beyond the snow line, testing basic predictions of the core accretion scenario. Large observing campaigns with the new generation of coronagraphic instruments will probe the populations and properties of gas giants at large orbital separations. These instruments and ALMA will provide a systematic census of structure in protoplanetary disks. Radial velocity instruments are now targeting the 0.1 m/s sensitivity needed to detect the reflex motion induced by Earth-like planets around Sun-like stars, a challenge that requires understanding and mitigating astrophysical sources of Doppler noise. JWST will provide a huge leap in sensitivity for transit spectroscopy of relatively cool planets, including many targets identified by TESS, allowing radically new insights into the composition and structure of exoplanet atmospheres. Phase curves may also be possible if relaxation of operational constraints currently under consideration is possible. In the longer term, WFIRST's microlensing census of planets beyond 1 AU will perfectly complement Kepler's census of compact systems, and WFIRST will also be able to detect free-floating planets unbound from their parent star. Coronagraphic instruments on 20-30 meter telescopes will sharpen the sensitivity and angular resolution of direct imaging searches and spectroscopic characterization of gas giants, while the WFIRST coronagraph is expected to push spectroscopy to the regime of Neptunes and super-Earths, and to demonstrate the technology that would eventually allow images and spectra of habitable worlds around nearby stars.

PHYSICS OF THE UNIVERSE: UNDERSTANDING SCIENTIFIC PRINCIPLES

Building on discoveries of the 1990s, the first decade of the 21st century saw the establishment of a "standard cosmological model," ΛCDM, incorporating cold dark matter, a cosmological constant, a flat universe, and Gaussian primordial fluctuations from inflation. Observations since 2010 have tested this model far more stringently than before, with new physical phenomena and redshift domains and greatly improved measurement precision. CMB data from WMAP, the Atacama Cosmology Telescope (ACT), the South Pole Telescope (SPT), and, especially, the Planck satellite have confirmed ΛCDM predictions in exquisite detail, including the long series of acoustic oscillation peaks imprinted by primordial sound waves, the polarization power spectrum expected for adiabatic initial conditions that arise from quantum fluctuations during inflation, and a 40 σ standard deviation detection of the lensing of CMB fluctuations by clustered foreground dark matter (Figure 1.3). One fundamental result is a clear demonstration of "tilt" in the large-scale power spectrum, confirming the inflationary prediction of a small departure from "generic" scale-invariant fluctuations.

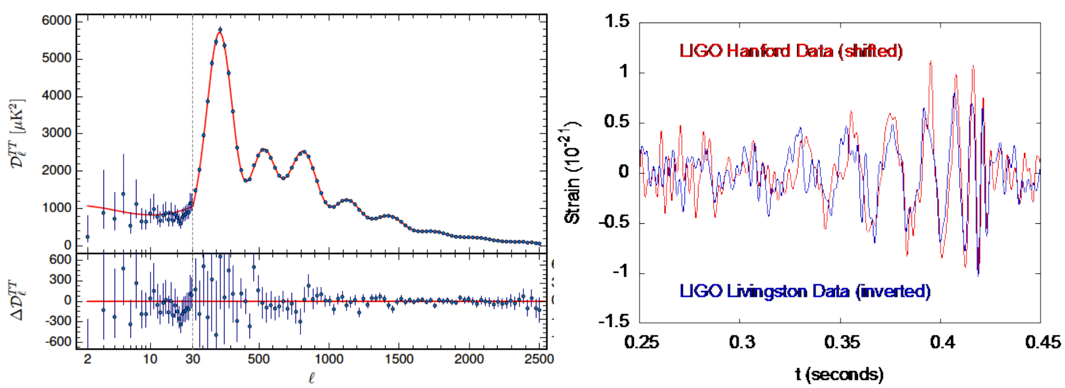

FIGURE 1.3 (*Left*) The power spectrum of temperature fluctuations measured by the Planck cosmic microwave background satellite. This spectrum exhibits a flat plateau at large angles (left side of plot) and a series of oscillations imprinted by primordial sound waves, in excellent agreement with the predictions of the cosmic inflation model shown by the red curve. Differences between the model and the data, shown in the lower panel, are generally smaller than the remaining observational uncertainties. The paper, Planck Collaboration XIII (2016), will be published in *Astronomy and Astrophysics* in 2016. (*Right*) The "chirp" of gravity waves measured by the advanced Laser Interferometer Gravitational Wave Observatory (LIGO) detectors from a merger of two 30 solar mass black holes at a distance of 1.3 billion light years. Red and blue curves show measurements from the detectors in Hanford, Washington, and Livingston, Louisiana, respectively. Oscillations become more rapid as the two black holes lose orbital energy and spiral together, ending when their event horizons coalesce and the new, more massive black hole "rings down" to quiescence. At their maximum strength, these gravitational waves stretch and squeeze the 4 km arms of the LIGO detectors by distances of 4×10^{-18} meters, 1,000 times smaller than the nucleus of an atom. SOURCE: (*Left*) Courtesy of ESA and the Planck Collaboration. (*Right)* Courtesy of Neil Cornish, Montana State University.

At lower redshifts, baryon acoustic oscillation (BAO) measurements from the Sloan Digital Sky Survey (SDSS) have allowed 1 percent determinations of the absolute cosmic distance scale at $z \approx 0.6$ and the first precise (2-3 percent) determinations of the expansion rate at high redshifts, $z \approx 2.5$. Homogeneous analyses of large supernova data sets have achieved 1-2 percent measurements of the relative distance scale over the range $0 < z < 0.8$ and lower precision measurements out to $z \approx 1.4$. The ΛCDM model reproduces these percent- or subpercent-level measurements of the cosmic expansion history from the recombination epoch to the present day. The model also predicts the history of dark matter clustering, which can be measured with gravitational lensing and galaxy clustering. Here, the agreement with observations is less clear, and the level of systematic uncertainties in the measurements is higher. There is also some tension between the values of H0 inferred from CMB and BAO data and those inferred from local distance ladder measurements.

As anticipated by NWNH, direct and indirect searches for dark matter have now achieved sufficient sensitivity to probe the core parameter space of broad classes of weakly interacting massive particle (WIMP) theories, such as those based on minimal supersymmetric extensions of the standard model of particle physics. The Fermi γ-ray satellite has been especially important because it detects photons in the energy range expected for typical WIMP annihilation channels, and it has deep, full-sky coverage. While there have been tantalizing claims of possible dark matter annihilation signals from the galactic center or from other galaxies or clusters, none of these signals is convincingly distinct from astrophysical sources, and the absence of signals from nearby dwarf galaxies sets interesting limits on WIMP annihilation cross sections. Underground direct detection experiments have yielded some claimed signals, but none of these have yet convinced the community as a whole, and other experiments are now ruling out significant regions of the supersymmetric particle parameter space. The Large Hadron Collider (LHC) has confirmed, with the dramatic discovery of the Higgs boson, a central pillar of the standard model of particle physics, but it has not yet shown evidence for supersymmetry or other standard model extensions that could explain dark matter.

Neutrino astrophysics has seen major advances (and the 2015 Nobel Prize in physics), including precise measurements of many of the parameters that describe the neutrino sector. Upper limits on neutrino mass from cosmological data are now approaching the lower limits set by neutrino oscillation data. The most dramatic recent development in neutrino astronomy is the IceCube experiment's detection of several dozen neutrinos in the peta-electronvolt (PeV) energy range, with arrival directions spread over much of the accessible sky. These are the first known astrophysical neutrinos from sources other than the Sun and Supernova 1987A, and their discovery opens the view to new messengers from the high-energy universe.

The most dramatic astronomical development of the century thus far is the detection of gravitational waves from merging black holes at a distance of 400 Mpc, during the first science run of the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) (Figure 1.3). This discovery follows decades of work to build instruments that can measure displacements 10,000 times smaller than an atomic nucleus, pushing the extremes of quantum optics, mechanical engineering, and signal processing. NWNH anticipated detection of gravitational waves this decade based on improving sensitivity of LIGO and pulsar timing experiments. Nonetheless, the detection of such a strong signal so early in advanced LIGO operations is startling. This discovery confirmed some of the most exotic predictions of Einstein's theory of general relativity, and it demonstrated that 30 solar mass black holes exist and form close binary systems, that black hole mergers produce gravitational wave bursts that match the predictions of numerical relativity simulations and analytic calculations of the merged remnant's ringdown, and that the interferometric methods pioneered by LIGO are up to the challenge of detecting astrophysical sources of gravitational waves. Most importantly for the future, this discovery strongly suggests that sources within LIGO's sensitivity range are fairly common and that gravitational wave observations will rapidly open a new window on some of the most energetic phenomena in the cosmos. Space-based gravitational wave observatories can probe different phenomena in frequency ranges inaccessible from the ground, and they can test general relativity predictions of black hole spacetimes at extremely high precision.

Many improvements are expected over the next 5 years, which may consolidate or challenge the current understanding of the physics of the cosmos. CMB experiments have set their sights on detecting the distinctively twisted polarization pattern induced by primordial gravitational waves, which would directly probe physics during an era when today's observable universe occupied a volume smaller than a grapefruit. The ongoing Dark Energy Survey (DES) and Subaru Hyper-Suprime Camera (HSC) survey will sharpen weak lensing measurements of matter clustering to the 1 percent level, comparable to current measurements of the expansion history. The Dark Energy Spectroscopic Instrument (DESI), slated to begin observations in 2019, will map the three-dimensional distribution of tens of millions of galaxies, yielding finer and more detailed measurements of expansion and structure growth over the past 10 billion years. New underground dark matter experiments (Super-CDMS, LUX-ZEPLIN, ADMX-Gen2) are expected to achieve order-of-magnitude gains in sensitivity to the most widely investigated candidates for particle dark matter. The higher operating energy and increased luminosity of the LHC make it sensitive to previously undetectable particle species. A convincing discovery of dark matter could come from these experiments any day, or not at all. IceCube will continue to build its sample of PeV neutrinos, while more densely sampled or larger area detectors will expand the reach of neutrino experiments to lower and higher energies. Analyses of several LIGO events are already in the works, and coordinated programs of follow-up for associated electromagnetic events are under way. By decade's end, a far more comprehensive view of the gravitational wave universe will be complete.

THE LARGER SCIENCE PROGRAM

The NWNH science themes represent three slices from the broad panorama of astronomical research. Exciting advances have occurred in many other fields of astronomy and astrophysics, and just a small selection is summarized here.

The fields of stellar astrophysics and stellar populations have been transformed by asteroseismology measurements from Kepler and by highly multiplexed spectroscopic surveys of stellar radial velocities and chemical compositions. Kepler's superb photometric precision and time sampling have yielded asteroseismic signals for many thousands of stars, allowing measurements of their internal structure and rotation profiles, and even the strength of their core magnetic fields. These measurements provide an unprecedented look at the inner life of stars. Combined with composition measurements, Kepler asteroseismology allows determination of stellar ages with an accuracy of 10 to 20 percent, adding a new dimension to studies of galactic structure. The SDSS APOGEE survey has mapped the multi-element abundances of 100,000 red giant stars across the full span of the Milky Way, finding patterns that reveal the inward and outward migration of stars by many kiloparsecs over the life of the galactic disk. ALMA has opened new windows on the study of the mass loss in evolved stars, and its sensitivity, resolution, and millimeter-wave spectroscopic capabilities are already having an impact on stellar astrophysics with detailed chemical, as well as dynamical, studies of evolving stars and planetary nebulae.

Other observations have mapped extremes of stellar properties and stellar fates. Programs that sift through stellar samples to identify the most chemically primitive stars have found some with heavy element abundances 1,000 to 10,000 times lower than the Sun's. The pattern of abundances in these metal-poor stars, including enhanced levels of carbon relative to other elements, provides clues to the physics of the first stars and the earliest stellar explosions. The Wide-Field Infrared Survey Explorer has revealed a large population of "Y dwarfs," objects with masses below the hydrogen-burning main sequence and surface temperatures below about 500 K. One such Y dwarf has an effective temperature of only 250 K, cooler than Earth; recently, two brown dwarfs in a binary have been found only 2 parsecs away, making these brown dwarfs some of the closest "stars" to the Sun.

At another extreme, measurements of relativistic time delay have identified two neutron stars with masses of 2.0 solar masses, and uncertainties of a few percent, eliminating many theories of the equation-of-state of nuclear matter. Supernova surveys with robotic telescopes, including the Palomar Transient Factory (PTF) and the All Sky Automated Survey for Supernovae (ASAS-SN), have uncovered many new classes of stellar explosions, including events that are 10 times fainter or several hundred times brighter than canonical supernovae. These discoveries challenge the standard picture of supernova physics. Other studies of early light curves and pre-explosion environments suggest that even the conventional Type Ia supernovae may well be a mix of two populations, powered by single- and double-degenerate explosions, respectively. X-ray observations of element distributions in supernova remnants, from the Chandra X-ray Observatory and the Nuclear Spectroscopic Telescope Array (NuSTAR) Explorer satellite, suggest clumpy and asymmetric explosion morphologies, providing a new testing ground for three-dimensional supernova calculations. PTF, ASAS-SN, and the Swift gamma-ray satellite have also begun to discover substantial numbers of tidal disruption events, in which a star is effectively turned inside out by passing too close to the supermassive black hole at its galaxy's center.

Supermassive black holes remain a central theme of observations at many wavelengths, especially the high energies that probe physical conditions close to the event horizon. Spectroscopy, reverberation mapping, and microlensing variability studies using Chandra, XMM-Newton, and NuSTAR have confirmed key aspects of the long-standing theoretical picture of accretion disks at a few tens of gravitational radii, although remaining puzzles may provide clues to the inner structure of accretion flows. ALMA has also yielded direct kinematic measurements of the mass of supermassive blackholes in nearby galaxies with a precision better than HST. Results from the Fermi Gamma-ray Space Telescope show that the extragalactic gamma-ray background is dominated by blazars, in which supermassive black hole accretion powers highly beamed relativistic jets. Some of Fermi's most dramatic results have come from our own galactic center, where a pair of giant gamma-ray bubbles spanning nearly 90 degrees of the sky (40,000 light years) suggest that the Sgr A* black hole was a far more luminous active galactic nucleus some 1-2 million years ago, pumping enormous energy into its surroundings. X-ray "echo mapping" of the galactic center, based on more than a decade of Chandra data, implies outbursts of activity within just the last few centuries, with the X-ray luminosity of Sgr A* flaring to a million times its present value. At millimeter wavelengths, coordinated observations with the global Event Horizon Telescope are approaching the extraordinary angular resolution needed to image the shadow of the Sgr A* event horizon, and they are already constraining the black hole spin and the physical structure of its accretion flow.

In addition to mapping the $z > 6$ galaxies of cosmic dawn, surveys from HST, Spitzer, Herschel Space Observatory, Chandra, ALMA, and ground-based optical telescopes have provided a much more detailed account of galaxy evolution through the epoch when the majority of stars in the universe formed. These observations reveal the often complex connections among stellar mass, star formation, gas content, morphology, size, metal abundance, and nuclear activity. At nearly all redshifts, stars form most effectively within dark matter halos that are similar in mass to the Milky Way's (roughly a trillion solar masses), and galaxies in more massive halos have largely ceased forming stars. The mechanisms that quench star formation—especially the relative importance of central black holes, stellar bulge formation, gas stripping, and "strangulation" of fresh gas accretion—remain hotly debated. Circumgalactic gas is both the reservoir that feeds galaxy growth and the repository of material ejected by galactic winds. Large programs with HST at low redshift and the Keck Observatory telescope and European Very Large Telescope (VLT) at high redshift have mapped the distributions of hydrogen, carbon, oxygen, and silicon in the circumgalactic medium, using ultraviolet absorption lines in the spectra of background quasars. ALMA has been used to observe CII and CO in order to measure the dynamics of galaxies at high redshift (z~6). These observations show that most star-forming galaxies are surrounded by large reservoirs of cool gas, comparable in mass to their stellar disks. Even the million-degree halos of hot gas that surround quenched elliptical galaxies are found to harbor large amounts of cool gas within them. Chandra and XMM-Newton observations have mapped the massive hot gas halo of the Milky Way, which imprints X-ray absorption lines on the spectra of bright background sources.

In the local universe, surveys using integral field spectrographs are providing detailed and unified maps of the stellar populations, chemical enrichment, gravitational dynamics, and gas flows in large samples of nearby galaxies spanning a wide range of properties. These observations provide direct insights into the ecology of galaxies, the physics of star formation, and the origin of galactic winds, and they provide a new testing ground for cosmological simulations of galaxy formation. Building on discoveries from the SDSS, the first 2 years of data from DES have revealed at least 15 new satellite companions of the Milky Way that are too faint or too diffuse to have been detected in previous sky surveys. These systems provide clues to the assembly history of our galaxy, tests of the properties of dark matter and the physics of low mass galaxies, and potential sources for the detection of dark matter annihilation into gamma rays. The Dragonfly telescope, an innovative array of telephoto lenses designed to produce highly uniform images over large areas, has discovered a population of "ultra-diffuse" dwarfs in nearby clusters, a new class of galaxies whose origin is not yet understood. In previous observations, these galaxies were literally too big to see.

This summary has emphasized observational developments, but theoretical work underpins the analysis and interpretation of many of these observational programs, and it is ultimately the means by which to go from empirical measurements to knowledge of the workings of nature. The discovery of gravitational waves followed decades of work on expected event rates and signal forms and a decade of extraordinarily rapid progress in numerical relativity calculations of black hole mergers, which show remarkable agreement with the first detection of this phenomenon. The design of cosmological surveys, from DES to WFIRST, relies heavily on theoretical optimization methods, and the inference of cosmological parameters from these experiments often involves large simulation programs that create mock data sets with realistic treatments of nonlinear gravitational clustering and bias between galaxies and dark matter. The powerful constraints inferred from CMB measurements also rely on sophisticated theoretical modeling and highly optimized computational and statistical methods. Advances in computational power and algorithms have allowed hydrodynamic simulations of galaxy formation to reach much greater levels of realism, resolving critical processes of stellar feedback on scales of a few parsecs while tracking the growth of primordial fluctuations into a Milky Way–like galaxy. Relative to previous generations, current simulations are much more successful at reproducing the observed properties and evolution of galaxies, and they are playing a key role in interpreting new observations of galactic outflows and circumgalactic gas.

On stellar scales, multiple groups around the world are now performing three-dimensional simulations of supernova explosions with increasing levels of sophistication, yielding new insights into the complex and long-standing puzzles of core collapse and thermonuclear supernova mechanisms. Kepler data have stimulated a burst of theoretical work on asteroseismology of red giants, which enables the Kepler measurements to probe the internal structure, rotation, and magnetic fields of evolved stars. The extraordinary diversity of Kepler planetary systems has stimulated theoretical investigations of the dynamical stability of tightly packed orbital configurations, the mechanisms that regulate orbital radii and eccentricity, and the physics that governs habitability. Transit spectroscopy and direct detection measurements draw on increasingly sophisticated models of planetary atmospheres, which include detailed molecular chemistry, cloud formation, and circulation flows driven by stellar irradiation.

The significance of theoretical developments often takes many years to emerge, as once speculative ideas are tested by observations enabled by new technology. The high-precision cosmological measurements of this decade, for example, provide spectacular confirmation of theoretical work on cosmological perturbations and non-baryonic dark matter from the 1970s and 1980s. The detection of gravitational waves confirms Einstein's once-radical views of spacetime and gravity from the early 20th century. The interpretation of Kepler discoveries is heavily influenced by classic work on celestial mechanics and by theoretical descriptions of planet formation and migration first advanced 30-50 years ago. The interaction between theory and observations sometimes takes surprising forms, such as the recent suggestion that the anomalous clustering of the orbits of newly discovered solar system bodies may be explained by the existence of a ninth planet that is 10 times more massive than Earth, which presently orbits hundreds of astronomical units from the Sun. If the existence of "Planet IX" is confirmed by direct detection, it will write a new chapter in the history of the solar system, echoing the discovery of Neptune through its gravitational effects nearly two centuries ago.

TECHNICAL ADVANCES

The time since the release of NWNH has seen great progress in the technological underpinnings of astronomy. Advances abound, so the committee only presents examples of this progress below.

In gravity wave astronomy, the impressive early results from the LISA Pathfinder Mission have demonstrated the key technologies needed for a future space mission to cover the source-rich megahertz portion of the gravitational wave spectrum, and of course the outstanding results from LIGO demonstrate the success of the underlying technological approach.

In X-ray astronomy, in both Europe (as part of the Athena technology program) and in the United States (as a continuation of Con-X technology), there has been the demonstration of sub-10-arcsec lightweight X-ray mirrors; the successful development of high resolution, high-efficiency X-ray gratings that allow an order of magnitude improvement on the performance of the Chandra and XMM gratings; and the demonstration of electronvolt resolution imaging X-ray spectrometers, as shown by the successful operation of the Hitomi soft X-ray spectrometer. NuStar has utilized broadband (5-80 keV) multilayer focusing optics and low background imaging hard X-ray detectors. High-speed (100 ns) silicon drift detectors have been developed for the NICER (Neutron Star Interior Composition Explorer) mission, and there has been a major improvement in X-ray polarimeters. There have also been major developments in gamma-ray technology, including major advance in Si strip technology, as pioneered by Fermi and the LHC, and in CdZnTe technology.

In survey cosmology, which is central to studies of dark energy and cosmological parameters, the principal technical advances have been increasing power of large format detectors and highly multiplexed fiber systems. The DES uses a 520 megapixel charge-coupled device (CCD) camera on the 4-m Blanco Telescope at the Cerro Tololo Inter-American Observatory, and it will eventually be superseded by the 3.2 gigapixel camera being built for the Large Synoptic Survey Telescope (LSST).

The maturation of H4RG near-infrared detectors, with four times the pixel count of the previous generation H2RGs, has had a major impact on the design of WFIRST. For redshift surveys, the 1,000-fiber spectrographs used for the SDSS-III Baryon Oscillation Spectroscopic Survey (BOSS) will be superseded at decade's end by the 5,000-fiber DESI for the 4-m Mayall Telescope at the Kitt Peak National Observatory. In CMB studies, individual detectors are already at the quantum sensitivity limit, and higher sensitivity is being achieved by building ever larger and more integrated arrays of bolometers. This approach has led to substantial gains, especially for CMB polarization experiments where the signals being measured are one or more orders-of-magnitude down from the temperature anisotropy.

Previous generations of high-contrast imager designs were optimized for ideal unobscured apertures. These solutions would not work for the 2.4-m obscured WFIRST pupil. Rapid development in response to this led to multiple concepts for coronagraphs that control the diffraction pattern from the secondary mirror and its supports, either with shaped-pupil masks, phase-induced amplitude apodization (PIAA) mirrors, or multiple deformable mirrors. Laboratory demonstrations of these technologies show contrast and stability levels sufficient to detect extrasolar planets with WFIRST.[2]

Dedicated high-contrast ground-based exoplanet imaging instruments, such as the Gemini Planet Imager, the VLT SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) facility, and the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) testbed, are now operational, producing significant exoplanet discoveries and proving techniques and technologies that will be needed for future high-contrast imagers on extremely large telescopes or in space.

Powerful infrared spectrographs, such as the Keck MOSFIRE multi-object near-infrared spectrograph, open up new scientific possibilities. By accessing the Doppler-shifted emission peak of galaxies, they can carry out large surveys of high-redshift galaxies on a scale previous restricted to

[2] NASA, 2015, Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report, Science Definition Team and WFIRST Study Office, https://arxiv.org/ftp/arxiv/papers/1503/1503.03757.pdf.

visible-light programs. The successors to the SDSS, such as the Dark Energy Camera, are producing revolutionary science and showing the future potential of LSST. Massively multiplexed optical spectrographs (Hobby-Eberly Telescope Dark Energy Experiment, DESI, and Subaru Prime Focus Spectrograph) will bring similar scales to spectrographic surveys for BAO dark-energy measurements and other programs.

Adaptive optics (AO) systems continue to increase in capability, with fully operational laser guide star systems on both Keck telescopes, adaptive secondary mirror systems with high performance on both the Large Binocular Telescope and Magellan (including some visible-light capabilities, albeit limited to bright stars), and the wide-field multi-conjugate AO system on Gemini South.

At radio wavelengths, advances in digital signal processing technology combined with reductions in cost are making possible arrays composed of a large number of relatively small antenna elements, giving large fields of view with large collecting areas. These arrays enable comprehensive sky surveys with implications for cosmology, for the study of transients, and for charting the evolution of galaxies and clusters over cosmic timescales.

It is worth noting, however, that the above advances in ground-based astronomy technologies were set in motion in an era when NSF supported a variety of instrumentation programs, including the Telescope Systems Instrumentation Program to build instruments for large telescopes. In the remainder of this decade, with the exception of LSST, the Department of Energy-funded dark energy program building the DESI spectrograph, and some smaller-scale programs funded by the Major Research Instrumentation Program, ground-based optical and infrared instrumentation will likely slow significantly.

2

Programmatic Context

In addition to the scientific progress described in the previous chapter, considerations of programmatic context are a factor in the committee's assessment of the agencies' response to *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) and in the committee's recommendations for the remainder of the decade. These include the overall fiscal landscape and developments in three components of the overall program: ground-based activities, space-based activities, and activities with close connection to physics, such as particle astrophysics, gravitation, and cosmic microwave background (CMB) studies. These three programmatic areas are closely linked to the National Science Foundation (NSF), NASA, and the Department of Energy (DOE), respectively, but have considerable overlap and benefit from synergy between them. In each of these areas, the committee also considered developments outside the United States. In this report, as in NWNH, the committee frequently refers to "balance" in the astrophysics program; therefore, an understanding of the committee's interpretation of balance, as discussed in NWNH, is considered to be an important part of the context. Finally, this chapter concludes with a brief discussion of the state of the profession.

THE FISCAL LANDSCAPE

NWNH emphasized the importance of a balanced decadal program with a mix of large and medium-scale initiatives and a strengthening of core research infrastructure through individual grants and support for instrumentation, technology development, and theory.

For both ground and space, the top-ranked large initiative (Large Synoptic Survey Telescope [LSST] and the Wide-Field Infrared Survey Telescope [WFIRST], respectively) was a low-technical-risk facility with a relatively broad science program. WFIRST was envisioned by NWNH to be a moderate-cost mission that could be executed on a relatively short timescale, and not a "flagship" mission. The second-ranked large initiatives for the ground and for space (Mid-Scale Innovations Program [MSIP] and Explorer augmentation, respectively) were programs intended to support intermediate-scale projects that could respond quickly to new scientific and technical opportunities. The allocation of resources among the different scales was done within the framework of budget scenarios for the agencies. Relative to the budget assumptions adopted by NWNH, which were more optimistic than the budget guidance given to the survey committee by the agencies, the actual budgets of the NSF Division of Astronomical Sciences (NSF-AST) and the NASA Astrophysics Division (NASA-APD) have been considerably lower than projected.

For NSF-AST, NWNH based its recommended program on a scenario in which the NSF-AST budget approximately doubled in real-year dollars[2] over the course of the decade. NSF input to NWNH suggested a more pessimistic scenario, with a budget approximately flat over the decade in fiscal year

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

[2] Real-year dollars are unadjusted for inflation.

(FY) 2010 (inflation-adjusted) dollars.[3,4] NWNH noted that in this scenario "the only way there can be any significant new initiative is through very large reductions in the funding for existing facilities and budget lines."[5] The NSF-AST budget through the first half of the decade has been notably worse than even this more pessimistic scenario: approximately flat in real-year dollars, with a substantial erosion of purchasing power over time (Figure 2.1). Recognizing the need to identify funds for new initiatives, NSF executed in 2012 the NWNH recommendation of a second senior review by carrying out a broad Portfolio Review of the NSF-AST program.

FINDING 2-1: The NSF-AST budget through the first half of the decade has been approximately flat in real-year dollars. This budget reality is somewhat lower than that baselined by NSF for NWNH (approximately flat in inflation-adjusted dollars) and significantly lower than that assumed by NWNH (doubling in real-year dollars).

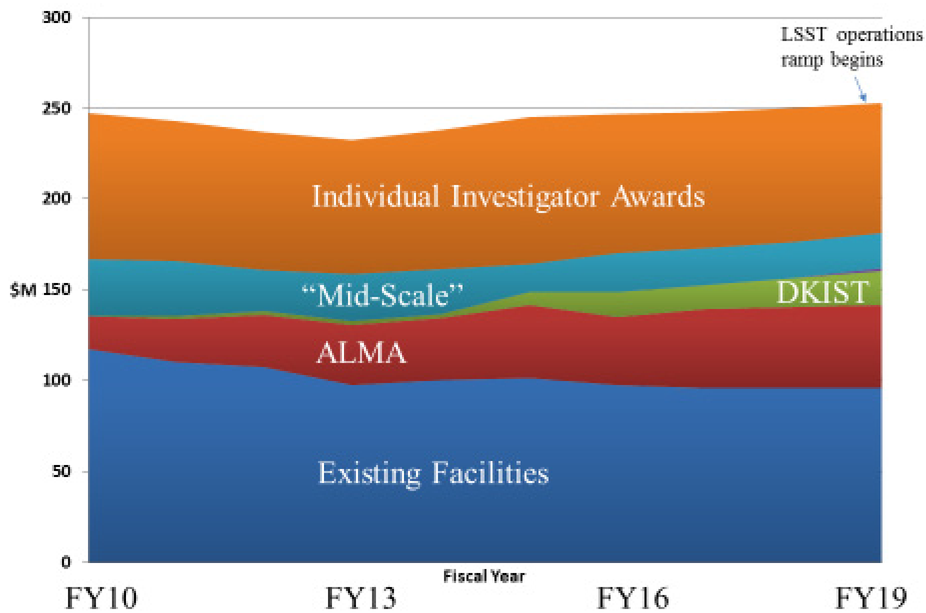

FIGURE 2.1 The NSF-AST budget from FY2010 to FY2019. The budget is divided into operations costs for existing facilities, operations costs for the major new facilities ALMA and DKIST, and support available for midscale programs and individual investigator grants. Values past FY2016 are based on the NSF's 2017 discretionary portion of its budget request. The chart assumes only divestments already in place or planned in FY2017 budget request take effect. "Mid-Scale" includes the Mid-Scale Innovations Program, the University Radio Observatories, and Telescope Systems Instrumentation Program. Facility run-outs given are as specified in the 2017 budget request. The chart assumes a 1 percent per year AST increase in 2018 and 2019. NOTE: ALMA, Atacama Large Millimeter Array; DKIST, Daniel K. Inouye Solar Telescope; FY, fiscal year; NSF-AST, National Science Foundation Division of Astronomical Sciences; NWNH, New Worlds, New Horizons. SOURCE: Figure adapted from figure provided by James Ulvestad. Data from NSF.

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[3] NRC, 2010, *New Worlds, New Horizons*, p. 187.
[4] Inflation was assumed to be about 3 percent per year.
[5] NRC, 2010, *New Worlds, New Horizons*, p. 188.

For NASA-APD, NWNH assumed a flat budget in inflation-adjusted dollars. NASA-APD budget guidance to the survey committee was that the budget would remain flat in real-year dollars through the decade, implying a decrease in real purchasing power at the rate of inflation.[6] The sum of the James Webb Space Telescope (JWST) and APD budgets has roughly tracked this assumption during the first half of the decade (although it is projected to flatten in real-year dollars in the second half). However, the late-breaking schedule delay and associated cost increase for JWST have effectively delayed the availability of a funding wedge for new initiatives by about 4 years. In response to problems encountered in the development of JWST, NASA removed JWST management from APD and established a new, separate office (the James Webb Space Telescope Program Office) within the Science Mission Directorate responsible for completing the project. The JWST budget was also transferred to this new office. At the time that this was done, it was anticipated that the budget wedge created by the roll-off of JWST development activities as the project approached launch would be recombined with the APD budget. Thus, while the NSF-AST budget has been depressed well below NWNH expectations through the full decade, the NASA-APD budget has been shifted in time (Figure 2.2).

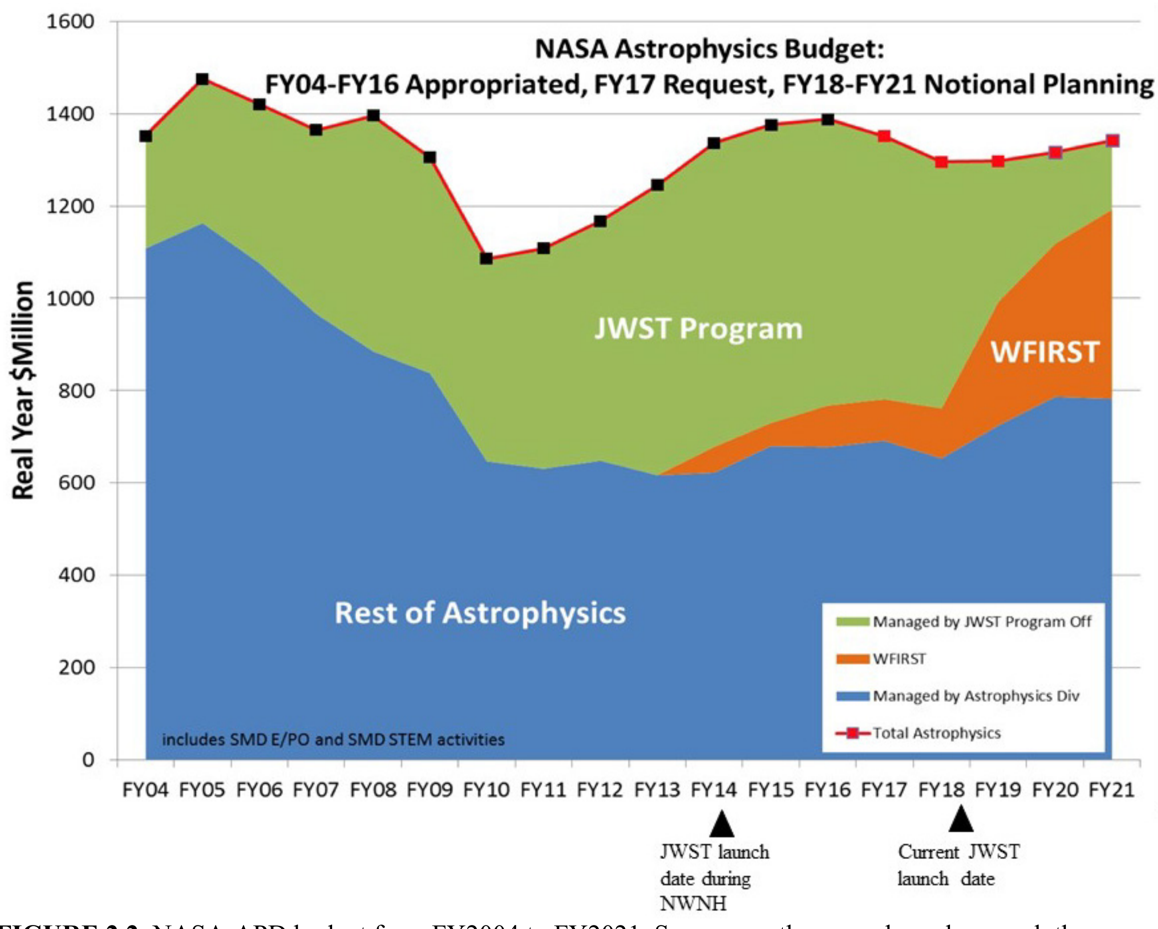

FIGURE 2.2 NASA-APD budget from FY2004 to FY2021. Squares on the upper boundary mark the sum of the JWST budget and the NASA-APD budget, with values for FY2017 and FY2018-FY2021 representing the administration request and the notional outyear planning budget, respectively. Expected dates for the JWST launch during NWNH and currently are indicated. NOTE: FY, fiscal year; JWST, James Webb Space Telescope; NASA-APD, NASA Astrophysics Division; NWNH, *New Worlds, New Horizons*. SOURCE: Figure adapted from a presentation by P. Hertz, NASA. Data from NASA.

[6] NRC, 2010, *New Worlds, New Horizons*, p. 187.

FINDING 2-2: For NASA-APD, NWNH assumed a flat budget in inflation-adjusted dollars. The actual combined budget for NASA-APD and JWST has roughly tracked this assumption. However, the late-breaking schedule delay and associated budget increase of JWST have delayed the availability of funding for new initiatives by about 4 to 5 years.

For DOE, NWNH based its budget assumptions on the 2009 High Energy Physics Advisory Panel (HEPAP) report,[7] considering that report's Scenario A, in which the total budget was constant in inflation-adjusted dollars, and Scenario C, in which there is a budget doubling over the decade in inflation-adjusted dollars. NWNH recommendations are based on the more optimistic scenario. For the first half of the current decade, the Cosmic Frontier budget line in real-year dollars increased by slightly more than 50 percent, so for the DOE program, the budget reality has been much closer to the baseline plan presented in NWNH than for the other agencies.

FINDING 2-3: At DOE, support for astrophysics has been strong, and the budget reality has been close to the baseline plan presented in NWNH.

GROUND-BASED ASTRONOMY AND ASTROPHYSICS

Optical/Infrared

The U.S. optical and infrared (OIR) system, with its unique mix of private and public facilities, continues to produce world-leading scientific results. The ground-based system is a powerful complement to space facilities; for example, the ground-based observations confirm many Kepler exoplanet candidates and allow measurements of their density, and ground-based observations provide critical data for dark energy parameter constraints. New instrumentation on 4- to 10-meter telescopes and new analysis techniques have continued to extend the capabilities of very large telescopes built in previous decades.

However, these successes occur against a landscape of challenges. NSF funding to support public observatories has eroded, and several have been closed and others are facing federal divestment to allow NSF to achieve its other goals. NSF funding for new instrumentation for OIR telescopes is also challenging to obtain, particularly with the termination of the NSF Telescope Systems Instrumentation Program (TSIP) that had previously provided both instrumentation funding and a channel for public access to powerful private facilities. As a result, the access of U.S. scientists to state-of-the-art instruments will decline over the remainder of the decade. The general astrophysics community no longer has access through TSIP to the powerful Keck telescopes and other 6-10 meter telescopes, and the last TSIP-funded instruments are coming online now; no new major capability is in development for Keck, and most U.S. observatories are in a similar situation.

Offsetting declining NSF support to some extent, other federal agencies have funded ground-based capabilities that meet their science needs, with cooperative ventures between DOE and NSF proving especially important. The Dark Energy Survey (DES) on the Blanco 4-m telescope, located at the Cerro Tololo Inter-American Observatory in Chile, represents a major advance in weak-lensing measurements of cosmic structure, and the Dark Energy Camera that DOE built for DES is one of the National Optical Astronomy Observatory's (NOAO's) most powerful instruments for community science. Through its support of the Sloan Digital Sky Survey's (SDSS's) Baryon Oscillation Spectroscopic Survey (BOSS) and Extended Baryon Oscillation Spectroscopic Survey (eBOSS) projects and, on a larger scale, the Dark Energy Spectroscopic Instrument (DESI), DOE is enabling giant galaxy redshift surveys for

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

precision measurements of cosmic acceleration and structure growth. DESI allows the Mayall 4-meter telescope at Kitt Peak National Observatory to remain a cutting-edge scientific facility following NSF divestment. DOE is building the LSST camera, which together with NSF Major Research Equipment and Facilities Construction (MREFC) funding of telescope construction has enabled LSST to stay on track for operations beginning in the early 2020s. The DOE science focus in these projects is on cosmology and neutrino physics, but the data sets produced by SDSS, DES, DESI, and LSST have applications across a wide range of astronomy and astrophysics. In addition to its direct funding of projects, DOE is playing a crucial role in sustaining the strength of the U.S. research community through its support of individual scientists and research groups.

Other significant support of ground-based astronomy comes from the Air Force Research Laboratory and private sources in their funding of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) project. Pan-STARRS has surveyed three-fourths of the sky (north of declination −30) approximately 60 times. However, funding exists only to make these archival survey data available to the community for 1 year. NASA continues to operate Pan-STARRS, but only in a mode optimized for finding near-Earth objects. NASA is also funding a new instrument and associated operations costs for the Wisconsin/Indiana/Yale/NOAO (WIYN) telescope in support of exoplanet studies. These agencies' support of ground-based programs remains focused on their own science interests and, to a significant extent, on large-scale programs.

The international (U.S.-managed) Gemini Observatory was an area of concern for NWNH. With the deployment of the Gemini Planet Imager and plans for a high-resolution optical spectrograph, the Gemini instrumentation suite is becoming more capable, and the management structure has been changed to be more responsive to community concerns. The greatest change in U.S. access to Gemini came in 2012 with the withdrawal of the United Kingdom from the partnership, which resulted in the U.S. share of Gemini going from 50 to 65 percent with no increase in the U.S. contribution.

At the time of NWNH, projects for the next generation of telescopes were beginning. Referred to as Extremely Large Telescopes or Giant Segmented Mirror Telescopes (GSMTs), these 20-40 m instruments will be revolutionary for most of the science themes discussed here. Progress toward a U.S. GSMT is discussed in the section "The Ground-Based Program—Large Scale" in Chapter 3.

The European Very Large Telescope (VLT) and the Japanese Subaru telescopes continue to be upgraded with instrumentation programs significantly more ambitious than those of any U.S. public or private 8- to 10-meter facility. The European Extremely Large Telescope (E-ELT), a 39-meter-diameter aperture telescope under construction on Cerro Armazones in Chile, will be larger than any other planned optical-infrared telescope in the world. The E-ELT program was approved by the European Southern Observatory (ESO) in 2012; ground breaking and site preparation began in 2014, proceeding to construction was approved in December 2014, and the first suite of instruments was approved in 2015. Science operations are expected to begin in 2026.

Radio

At the time of NWNH, the U.S. radio facilities were the Very Large Array (VLA), the Very Long Baseline Array (VLBA), and the Green Bank Telescope (GBT), all operated by the National Radio Astronomy Observatory (NRAO; managed by Associated Universities, Inc.); and Arecibo, operated by Cornell University; and university-operated radio facilities. The two major advances in the past half-decade are the completion of a major upgrade to the VLA, now known as the Karl Jansky Very Large Array (JVLA; completed in 2013), and the successful completion of the construction and first three cycles of observing by ALMA (construction completed in 2015). Both projects were completed within budget. Jointly operated by North America (through NRAO), Europe (through ESO), and Japan (through the JAO), ALMA is a new submillimeter/millimeter array located in the Chajnantor plateau in northern Chile, having been prioritized as the second large-class priority of the 1991 decadal survey. The first three cycles of observing with ALMA have yielded ground-breaking discoveries in planetary science, the late stages of stellar evolution, galaxy dynamics, and the morphology and kinematics of the first galaxies. Meanwhile, the JVLA has enabled fundamental studies of the evolution of the gas content of galaxies and star formation in the Milky Way, among other studies. Additionally, a consortium led by the University of Massachusetts and INOAE (Mexico) achieved first light with the Large Millimeter Telescope (LMT), which promises new advances in the study of gas and dust in galaxies across cosmic time.

FINDING 2-4: The completion and successful operation of ALMA are a remarkable success and the culmination of significant investment by NSF through the MREFC program.

While NWNH recommended investment in a new millimeter survey telescope, CCAT, to complement ALMA, there has been no new funding to enable CCAT to proceed past an initial design stage (see Chapter 3).

Since NWNH, the NSF Portfolio Review has recommended that NSF divest from the VLBA and the GBT and that it subsume any further support of university radio observatories into the MSIP. As of October 2016, the VLBA and the GBT will be operated as stand-alone facilities—the Long Baseline Observatory (LBO) and the Green Bank Observatory (GBO), respectively—for 2 years with a decreasing fraction of support from NSF-AST and an increasing contribution from private sources and other government agencies. After recompetition, a new management consortium took over the operation of Arecibo. The Portfolio Review also recommended that NSF-AST consider divestment of Arecibo later in the decade; currently, its status is under discussion within NSF-AST.

Other radio instruments considered promising by NWNH include the Event Horizon Telescope (EHT), pulsar timing detections of gravitational waves (NANOGrav), and arrays for 21 cm cosmology (Murchison Widefield Array [MWA], Precision Array to Probe Epoch of Reionization [PAPER], and Hydrogen Epoch of Reionization Array [HERA]). The EHT is moving forward with combined support from MSIP and the Gordon and Betty Moore Foundation. NANOGrav has received combined support from MSIP and from the NSF Physics Division (NSF-PHY) as a Physics Frontier Center, from the Natural Sciences and Engineering Research Council in Canada and the Research Corporation for Scientific Advancement in the United States. The NANOGrav support includes funds for purchasing time on the GBT, although the future of GBT is uncertain and the loss of access to GBT would be very detrimental to NANOGrav. The MWA and PAPER low-frequency arrays are operating, and HERA has received funding for technology development from MSIP.

A major development for radio astronomy worldwide is the initiation of the international Square Kilometer Array (SKA) project. The United States is not a member nation, but through precursor activities is contributing to some aspects of the design of SKA Phase 1. Preliminary design and prototyping of Phase 1 is complete. It consists of two arrays, SKA-low, to be built in Australia, and SKA-mid, to be built in South Africa. The SKA headquarters will be in the United Kingdom. In China, construction of the Five hundred meter Aperture Spherical Telescope (FAST) began in 2011 with an expected completion date of 2016. Its design is similar to that of the 305-m Arecibo telescope. With its enormous collecting area, FAST will be the most sensitive telescope in the world. As of this writing, the United States does not have significant participation in these large international radio astronomy initiatives.

SPACE-BASED ASTRONOMY AND ASTROPHYSICS

Despite schedule delay and cost increase, JWST is now on track with a late 2018 launch to deliver science capabilities that will very much exceed those of the Hubble Space Telescope (HST). However, the delay and increased cost of JWST has led to delay in starting WFIRST, the top-ranked NWNH large space initiative. As a result, WFIRST had its Phase A start in 2016 and is working toward a launch in 2024-2026 rather than in 2020, as envisioned by NWNH. The Explorer program augmentation recommended by NWNH has also been delayed, with the first Small Explorers (SMEX) Missions +

Mission of Opportunity (MoO) Announcement of Opportunity issued in 2014 (see further discussion in the section “The Space-Based Program—Large Scale” in Chapter 4). The Nuclear Spectroscopic Telescope Array (NuSTAR) was launched in June 2012 and is providing astronomers with their first look into the high-energy X-ray universe. The Stratospheric Observatory for Infrared Astronomy (SOFIA) reached full operational capacity in February 2014 and provides unique capabilities for mid-to-far infrared spectroscopy. Two Explorers, the Transiting Exoplanet Survey Satellite (TESS; expected launch in December 2017) and the Neutron Star Interior Composition Explorer (NICER; expected launch in February 2017), are in development. LISA Pathfinder (LPF) was launched in December 2015 (NWNH assumed launch in 2012), and initial analysis shows it has been successful thus far. NASA continues to be a partner in the European Space Agency’s (ESA’s) Euclid observatory, which is slated for launch in 2020. NASA is also currently supporting five SMEX/MoOs.[8]

Recent developments in space-based astronomy in Europe and Japan are also having a significant impact on the U.S. program. At the time of NWNH, Euclid, the International X-ray Observatory (IXO), and the Laser Interferometer Space Antenna (LISA) were all NASA-ESA collaborations (and in the case of IXO, the collaboration included the Japan Aerospace Exploration Agency [JAXA]). Significant changes in the NASA-ESA context occurred around 2011 as the budgetary realities of the decade and their implications for implementation of NWNH became clear. ESA announced a “new approach” for its L-class (large) missions and formed European-led science teams to examine European-led affordable missions. This resulted in the Jupiter Icy moons Explorer (JUICE) mission, the Athena mission, and the gravitational wave theme, subsequently chosen for L1 (2022 launch), L2 (2028 launch), and L3 (2034 launch), respectively, by ESA.

Both LISA’s and IXO’s prioritizations in NWNH were based on near 50-50 partnerships between NASA and ESA; the impact of ESA’s decisions is discussed in the section “The Space-Based Program—Large Scale” in Chapter 4. However, in an effort to limit its exposure to the risks associated with collaboration beyond Europe, the committee was informed that ESA has instituted a 20 percent cap on the fraction of the budget of a mission provided through international collaboration.[9] The series of events surrounding the NASA-ESA efforts illustrate the complexities of long-term planning for international collaborative missions.

The Astro-H mission, now renamed Hitomi, is a collaboration between JAXA and NASA. It launched in February 2016 and, despite successful initial operations, underwent a catastrophic set of operational errors on March 26, 2016, and was declared lost by JAXA on April 28. Despite the failure of the satellite, one excellent data set, an observation of the Perseus cluster, was obtained. This observation confirmed the unprecedented energy resolution in the astrophysically important iron K-alpha line as well as the existence of a wide variety of temperature, ionization, abundance, and dynamical diagnostics in X-ray spectra and demonstrated this detector technology in space for the first time. JAXA has revised the Space Infrared telescope for Cosmology and Astrophysics (SPICA) concept, and it is being considered for launch in the late 2020s. An ESA group will propose a new SPICA concept to the ESA Cosmic Visions M5 call. LiteBIRD, a CMB mission with planned sensitivity to B-mode polarization at an inflationary tensor-to-scalar ratio of $r = 0.001$, is also in the planning stage. India’s first space-based dedicated astronomical observatory, Astrosat, was launched in September 2015 with five astronomical instruments onboard that provide simultaneous co-aligned ultraviolet to X-ray telescope coverage. Its widefield X-ray instrument provides large-area X-ray timing capability, restoring a capability previously provided by the Rossi X-ray Timing Explorer. In December 2015, China launched the Dark Matter Particle Explorer, the first Chinese space mission for astronomy and astrophysics and one of a series of planned space science

[8] SPHEREx, PRAXyS, IXPE, LiteBIRD (for U.S. participation), and GUSTO.

[9] Within Europe, ESA manages its budget with a 5-year horizon at levels agreed to by all member states. The levels can be changed only by unanimous vote, providing stability on this timescale. The committee was informed that in executing its missions, ESA funds the spacecraft and launch and cooperates with the member states to secure the scientific instruments.

missions. In July 2011, Russia launched the RadioAstron mission, a space-based radio telescope designed for very-long-baseline interferometry at centimeter wavelengths. The Spectrum-XG mission, featuring a wide-field X-ray telescope (eRosita) developed by Germany and a hard X-ray telescope (ART-XC) developed by Russia in collaboration with NASA's Marshall Space Flight Center, is currently scheduled for launch in 2017.

The technology for electromagnetic observations from space has improved in several ways—with programmatic implications since NWNH was written. Investment by NASA in mercury cadmium telluride (HgCdTe) detector development has resulted in wide-format infrared detectors that are background limited in space at temperatures that can be reached by passive cooling in high orbits. These arrays will be useful for wide-field infrared survey missions, including WFIRST. Rapid progress has been made in the design of pupil and focal plane masks for coronagraphs on telescopes with obscured apertures, including designs specifically for WFIRST-Astrophysics Focused Telescope Assets (AFTA). The starshade approach using an external occultor has also been significantly advanced. At X-ray energies, NuSTAR demonstrates the power of multi-layer coatings applied to highly nested, segmented glass X-ray mirrors. The X-ray calorimeter on Hitomi was providing unprecedented energy resolution in the astrophysically important iron K-alpha line, demonstrating this detector technology in space for the first time.

PARTICLE ASTROPHYSICS, GRAVITATION, AND THE COSMIC MICROWAVE BACKGROUND

NWNH noted that LISA would provide insight into the early growth of black holes and the cosmological history of galaxy formation and test general relativity with exquisite precession. The potential for transformative discoveries was highlighted: "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."[10] Gravitational wave detection is currently being pursued through four main efforts: ground-based interferometers (led by Advanced LIGO [Laser Interferometry Gravitational-wave Observatory]), pulsar timing arrays, space-based interferometers, and polarization measurements of the CMB. Funding for these programs comes from NSF-AST, NSF-PHY, NASA, and DOE. Advanced LIGO is part of a world-wide network of detectors under development, and operation of the two Advanced LIGO detectors in coincidence with the European Virgo and GEO600 detectors is intended to become routine. Long baseline interferometric detectors are also being planned in Japan (KAGRA) and India (LIGO India). The recent direct detection of gravitational waves by Advanced LIGO is a ground-breaking proof of principle for the interferometric technique, with implications for future directions on the ground and in space. The LISA Pathfinder (LPF) was launched in December 2015, whereas it was assumed by NWNH to be launched in 2012.[11] This is several years behind the schedule assumed by NWNH, but LPF results inform this report and will inform the next decadal survey. U.S. (NANOGrav) and international pulsar timing arrays continue to make precise timing observations, and recent limits on gravitational wave backgrounds at periods of months to years are beginning to challenge the simplest cosmological models. Measurements of the B-mode polarization patterns of the CMB are being made from the South Pole, high-altitude sites in Chile, and balloon platforms (see the sections "The Space-Based Program—Large Scale" and "The Space-Based Program—Medium Scale" in Chapter 4 for further discussion).

Particle astrophysics observatories and experiments in the United States are supported by NSF-PHY, NSF-AST, and DOE on the ground, and by NASA for suborbital and space missions. At the time of NWNH, the operating facilities for gamma-ray astronomy included Fermi, Swift, Integral, and AGILE in

[10] NRC, 2010, *New Worlds, New Horizons*, p. 201.

[11] LPF is an ESA-led mission, but the ST-7 component (colloidal thrusters and control system) are a U.S. contribution. NASA scientists are involved in the analysis of LPF data and will run the ST-7 segment of the mission.

space, and VERITAS, HESS, MAGIC, and Milagro on the ground. All of these continue to operate, except for Milagro, which has been succeeded by the High-Altitude Water Cherenkov Observatory (HAWC). HAWC construction in Mexico was completed in 2014 and it is now carrying out a high-sensitivity synoptic survey of the gamma-ray and cosmic ray sky at energies between 100 GeV and 100 TeV with a very large field of view.

NSF-AST participation in the Cherenkov Telescope Array (CTA) has not occurred because of budgetary constraints and programmatic choices vis a vis NWNH rankings. CTA, referred to as ACTA in NWNH, is the leading next-generation gamma-ray instrument designed to increase sensitivity by an order of magnitude as compared to the currently operating observatories VERITAS, HESS, and MAGIC. It would observe gamma rays over a wide range of energies (20 GeV to above 300 TeV). It is being developed by a large international consortium as an open observatory with one array in each hemisphere. In 2010, the U.S. Advanced Gamma-ray Imaging System effort merged into CTA, as recommended by NWNH. The NSF Major Research Instrumentation program funded a prototype SCT [Schwarzschild-Couder Telescope] in 2012 designed to perform near the theoretical limit for a Cherenkov Telescope. Construction of CTA is expected to start in 2017 with completion in 2024 (see the section "The Ground-Based Program—Large Scale" in Chapter 3 for further discussion).

In neutrino astronomy, IceCube, under construction at the time of NWNH, is funded in the United States by NSF-PHY and the NSF Division of Polar Programs. After IceCube's important discovery of peta-electronvolt (PeV) neutrinos in 2013, several upgrade plans are being considered. At ultrahigh energies (exa-electronvolt, EeV), where neutrinos produced by photo-pion production of ultrahigh-energy cosmic rays should be observed, a number of prototypes have been built, including the Askaryan Radio Array (ARA) and Antarctic Ross Iceshelf Antenna Neutrino Array (ARIANNA) in Antarctica and the balloon payload ANITA (Australian National Institute for Theoretical Astrophysics).

A number of observatories for cosmic rays of different energies are now operating. At lower energies, the leading detector is AMS-02 (Alpha Magnetic Spectrometer), which was deployed on the International Space Station (ISS) in 2011. AMS confirmed the PAMELA positron excess and is precisely measuring spectra of many cosmic ray primaries including anti-protons. The CALET, a JAXA-led electron calorimeter, joined AMS on the ISS in 2015, and in 2017 ISS-CREAM should also be deployed on the ISS to study cosmic rays at higher energies. Rare heavy primaries are currently being studied through the NASA balloon program with Super-TIGER. At higher energies, cosmic rays are studied by ground arrays up to 10^{20} eV. At the ultrahigh energies, the leading experiments are the Pierre Auger Observatory, covering 3,000 km^2 in Argentina and the Telescope Array (TA) observatory, covering 700 km^2 in Utah. During NWNH, the Particle Astrophysics and Gravitation panel recommended that Auger North be built if budgets allowed. The budgetary constraints did not allow this project to go forward, but an expansion of TA to match the size of Auger South, named Tax4, was recently approved by the Japanese funding agencies.

There has been considerable progress in CMB instrumentation and measurement since NWNH. WMAP published its final maps and cosmological analyses in 2013. Planck measurements have extended full-sky temperature and polarization maps to higher angular resolution, higher sensitivity, and greater frequency range, including high frequencies where galactic dust emission dominates. Planck temperature maps show the expected signature of gravitational lensing by foreground structure at a significance of 40 σ, allowing precise new tests of cosmological predictions for structure growth. Ground-based experiments, notably the South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT), complement Planck by reaching higher angular resolution, which is especially valuable for lensing and Sunyaev-Zeldovich measurements. In addition to showing beautiful agreement with the expected E-mode polarization signal, the ACTpol, SPTpol, BICEP2/Keck, and PolarBear experiments show clear detection of the B-mode polarization expected from gravitational lensing. BICEP2/Keck initially announced detection of large angle B-mode polarization from inflationary gravitational waves, but subsequent joint analysis with Planck indicates that this signal is dominated (and probably entirely explained) by polarized dust foregrounds. While the BICEP2 experience demonstrates the challenge of isolating the primordial gravity wave signal, many ground- and balloon-based experiments are pressing ahead to achieve the sensitivity and frequency coverage needed to detect large-angle B-modes at the level expected for inflationary tensor-to-scalar ratios as low as r ≈ 10-3. Current upper limits at r ~ 0.05 already rule out interesting inflationary models. Current and near-term efforts on the ground include SPTpol, SPT3G, ACTpol, Adv ACTpol, PolarBear, the Simons Array, BICEP3, the Keck Array, and ABS. Balloon-borne experiments include CASS, EBEX, Spider, and PIPER. NASA is supporting a near-term plan for higher sensitivity with observations from long-duration balloon flights. To date, several groups have made long-duration balloon flights around the South Pole with polarization sensitive radiometers at multiple wavelengths. In space, the CMB mission LiteBird has been selected for a SMEX phase A study as a MoO with JAXA.

CMB experiments receive support from the Physics and Astronomy divisions of the NSF, NASA, and the DOE Office of Science. DOE and NSF's Particle Physics Project Prioritization Panel (P5), a subcommittee of HEPAP, has recommended exploring a larger role for DOE in next-generation CMB experiments, drawing on the unique fabrication capabilities at the DOE national laboratories to implement a "Stage IV" CMB effort named CMB-S4.[12]

THE GOAL OF A BALANCED PROGRAM

A central and recurring theme of NWNH is "balance," and, although it is articulated as a guiding principle more than 30 times throughout the document, not all readers interpret balance in a consistent manner. Therefore, it is important to clarify the meaning of balance in this report. The committee interprets balance to refer to a viable mix of small, medium, and large initiatives on the ground and in space that optimizes the overall scientific return of the entire U.S. astronomy enterprise viewed collectively. It does not refer to a balance of wavelengths, nor of astronomy subtopics.

NASA's smaller core research programs include support for individual investigator grants, data management, theoretical studies, innovative technology development, the suborbital and balloon programs, archiving, and analysis of data realized from the missions. NWNH considered these initiatives "fundamental to mission development and essential for scientific progress"[13] that "must be protected from overruns elsewhere."[14] NWNH goes on to state: "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."[15] Moreover, NWNH highlighted "the impressive science value per dollar achieved with a healthy Explorer program,"[16] and as a result, an enhancement to the medium-scale Explorer program was its second-ranked space project recommendation. Hence, it was a clear conclusion of NWNH that balance is achieved, in part, through a diversified portfolio including large flagship missions, medium-scale Explorer missions and technology development, and smaller suborbital, data analysis, theory, and laboratory astrophysics programs.

In the NSF context, NWNH found that maintaining balance required wise stewardship of the NSF facilities portfolio, which involves both continued support for older facilities and the development and operation of newer ones. To accommodate new facilities and their operations costs, NWNH strongly advocated the senior review process "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

[12] Particle Physics Project Prioritization Panel, 2014, *Building for Discover: Strategic Plan for U.S. Particle Physics in the Global Context*, Department of Energy, Washington, D.C., p. 5, http://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_Interactive_060214.pdf.
[13] NRC, 2010, *New Worlds, New Horizons*, p. 219.
[14] NRC, 2010, *New Worlds, New Horizons*, p. 175.
[15] NRC, 2010, *New Worlds, New Horizons*, p. 219.
[16] NRC, 2010, *New Worlds, New Horizons*, p. 175.

facilities."[17] NWNH noted that there is a "trade-off 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"[18] and that this trade-off must be made while maintaining balance between large facilities initiatives and the many small research initiatives.

In summary, as envisioned by NWNH, balance requires that the uniquely capable major initiatives, with their high cost and low cadence, be complemented with both (1) innovative mid-scale initiatives, with their more modest cost and higher cadence, and (2) smaller initiatives, with their lower cost and higher cadence. NWNH considered such balance to be necessary to optimize the scientific return of U.S. investments and to maintain the health of the U.S. astronomical research community.

THE STATE OF THE PROFESSION

NWNH includes a discussion of the demographics of the astronomy profession, informed by a panel that reported to the subcommittee on state of the profession. NWNH noted continuing trends of a slowly increasing total number of astronomers, as measured by membership in astronomical societies and rates of degrees granted. Combined with flat or declining rates of tenure-track faculty positions available, this creates a concern about long-term job prospects, which was only partially offset by larger numbers of grant-funded positions and research staff positions. It was recognized that the skill sets required for astronomy research have application to non-astronomy employment, and NWNH recommended that the American Astronomical Society and the American Physical Society "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."[19]

NWNH also discussed underrepresented groups, noting that only 4 percent of astronomy Ph.D.s granted and only 3 percent of faculty are African American, Hispanic, or Native American. NWNH concluded that "agencies, astronomy departments, and the community as a whole need to refocus their efforts toward attracting members of underrepresented minorities to the field"[20] through targeted mentorship programs, joint internship programs with minority-serving institutions, family-friendly policies, and so on. Similarly, although there has been some overall progress on gender balance, only a small fraction of senior positions in astronomy are held by women—only 11 percent of full professorships were held by women as of NWNH.

The committee lacked the resources to explore demographic questions extensively, but there is little evidence that the situation for underrepresented groups has improved. Statistics from the American Institute of Physics[21] indicate that underrepresented minorities still account for only 3 percent of faculty positions in astronomy. The longitudinal study by the Committee on Status of Women in Astronomy[22] has only 10-year resolution but shows mild improvement in gender balance from 2003 to 2013, with the fraction of female faculty at all levels increasing from 13 to 17 percent. One encouraging result is that the rate of advancement from graduate student positions to tenure-track faculty positions is becoming more equal for women and men. However, critical issues remain, as highlighted by multiple recent news items about sexual harassment in academic research institutions.

The low rate of success for grant proposals is a serious a concern for the health of the profession. The Astronomy and Astrophysics Advisory Committee (AAAC), which advises NSF, NASA, and DOE

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[17] NRC, 2010, *New Worlds, New Horizons*, p. 32.

[18] NRC, 2010, *New Worlds, New Horizons*, pp. 14-15.

[19] NRC, 2010, *New Worlds, New Horizons*, p. 30.

[20] NRC, 2010, *New Worlds, New Horizons*, p. 127.

[21] American Institute of Physics, 2014, *African Americans & Hispanics among Physics & Astronomy Faculty*, Collage Park, Md., https://www.aip.org/sites/default/files/statistics/faculty/africanhisp-fac-pa-123.pdf.

[22] American Astronomical Society, 2014, *Status: A Report on Women in Astronomy*, http://www.aas.org/cswa/status/Status_2014_Jan.pdf.

on mutual agency issues within the fields of astronomy and astrophysics, is engaged in studying the reasons for the low grant success rate. No single cause has emerged, but this is a significant issue for the community because successful proposals are a key step towards tenure for grant-funded non-tenure-track positions and for training the next generation of scientists through graduate and post-doctoral fellowships at universities.

Chapter 5 of this report notes that the health of the profession is an important consideration in the planning for the next decadal survey.

3

Progress Toward NWNH Goals—Ground-Based Program

In this chapter, each of the "large," "medium," and "small" recommendations of *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) are considered in turn for the ground-based program. The progress that has been made toward NWNH goals is evaluated, including the programs adopted by the agencies and their plans for the remainder of the decade. Following the committee's evaluation of the individual NWNH recommendations, an overview of the ground-based program implementation is provided, and its balance is considered.

THE GROUND-BASED PROGRAM—LARGE SCALE

For reference, Table ES.3 of NWNH is reproduced below, listing the priorities for large-scale ground-based activities (Table 3.1). These included, in rank order, the Large Synoptic Survey Telescope (LSST), a Mid-Scale Innovations Program (MSIP) augmentation at the National Science Foundation (NSF), a Giant Segmented Mirror Telescope (GSMT), and the Atmospheric Cerenkov Telescope Array (ACTA).

LSST

LSST is an integrated survey system consisting of a new 8-meter class wide-field telescope, a 3.2 gigapixel camera with a 3.5-degree field of view, and an automated data processing system. LSST was NWNH's highest-ranked large-class ground-based initiative:

> 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 . . . 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.[2]

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.
[2] NRC, 2010, *New Worlds, New Horizons*, p. 223.

TABLE 3.1 Priorities for Large-Scale Ground-Based Activities from the 2010 Astronomy and Astrophysics Decadal Survey

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)	Page Reference
1. LSST - Science late 2010s - NSF/DOE	Dark energy, dark matter, time-variable phenomena, supernovas, Kuiper belt and near-Earth objects	Medium low	$465M ($421M)	$42M ($28M)	7-29
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	$93-200M		7-30
3. GSMT - Science mid 2020s - Immediate partner down-select for ~25% federal share	Studies of the earliest galaxies, galactic evolution, detection and characterization of planetary systems	Medium to Medium high	$1.1B to $1.4B ($257M - $350M)	$36M to $55M ($9M to $14M)	7-32
4. ACTA - Science early 2020s - NSF/DOE; U.S. join European CTA	Indirect detection of dark matter, particle acceleration and AGN science	Medium low	$400M ($100M)	Unknown	7-36

[a] The survey's construction-cost appraisals for LSST, GSMT, and ACTA are based on 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 GMT and $1.4 billion for TMT. Construction costs for GSMT could continue into the next decade, at levels up to $95 million for the federal share. The share for the U.S. government is shown in parentheses where different from the total.
[b] The survey's estimates 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 survey's appraisals for operations costs, in FY2010 dollars, are based on project input. The committee did not analyze these estimates in detail. 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 where different from the total.

SOURCE: National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., Table ES.3.

The top ranking of LSST in NWNH was "a result of its capacity to address so many of the identified science goals and its advanced state of technical readiness."[3] The expected scientific performance of LSST is essentially unchanged since NWNH, and there has been major progress programmatically. LSST is an excellent example of successful interagency cooperation, and it also leverages the relative strengths of public and private funding. NSF, which is the lead agency, supports the telescope and site facility, data management system, and education and public outreach, primarily via a Major Research Equipment and Facilities Construction (MREFC) award that was awarded in August 2014. The camera is provided by the Department of Energy (DOE), along with additional contributions from international partners. Authority to begin camera fabrication was granted by DOE in August 2015. Private support enabled the LSST project to retire several major risks through early fabrication of the primary/tertiary mirror and the secondary mirror blank, preliminary site preparation, and early sensor studies. Engineering First Light is planned in 2020, with the 10-year science survey commencing in late 2022.

[3] NRC, 2010, *New Worlds, New Horizons*, p. 225.

FINDING 3-1: LSST planning and construction have progressed well and are on schedule and within budget, successfully bringing together NSF funding, DOE funding, and private funding.

Data products of LSST will include the following:

- A nightly stream of ~10 million time-domain events detected and transmitted to event distribution networks within 60 seconds of observation;
- Catalogs of orbits for ~6 million bodies in the solar system; and
- Catalogs of ~37 billion objects (20 billion galaxies, 17 billion stars) and trillions of single-epoch detections.

Services and computing resources will be provided by data access centers to enable user-specified custom processing and analysis and interface software for higher-level science analyses. To support community-based brokering of the tremendous transient stream (advanced filtering services that add contextual information—for example, correlation with external catalogs or other alert steams, or additional analyses, for follow-up observation decisions and coordination), LSST will also provide an alert-filtering service.

LSST data will be transformational in scale and impact, especially for time-domain astronomy. However, the cost of operations and data analysis will be substantial. The estimated operations costs are about $50 million (in fiscal year [FY] 2023$) per year over the 10-year planned lifetime of the project, of which NWNH proposed that 70 percent be borne by the U.S. funding agencies—two-thirds by NSF and one-third by DOE.[4] The budgets presented to the committee by NSF's Division of Astronomical Sciences (NSF-AST) cannot accommodate LSST operating costs without a reduction in support for other activities, and the current individual investigator programs do not have the resources to carry out the scientific program enabled by LSST.

FINDING 3-2: Current projections for LSST performance and data products promise transformational scientific impact, as envisioned by NWNH. To realize the full scientific potential of this great new facility, funding that enables individual investigators and groups of investigators to deliver the scientific results will be critical.

MSIP

NWNH recommended the creation of a new Mid-Scale Innovations Program "that would enable moderate-scale projects to be frequently selected through peer review."[5] The survey committee likened this mid-scale instrumentation and facility program at NSF to NASA's Explorer program. This "mid-scale" level is that which falls between the limits of the NSF Major Research Instrumentation and MREFC programs, $4 million to $135 million. NWNH recognized the many highly promising projects in this funding category that might achieve innovative and timely scientific goals. NWNH recommended that the program be funded at an annual funding level of $40 million per year, or approximately double the amount being spent on projects in this size category through a less formal programmatic structure, and issue "roughly annual" calls for proposals.

As reported to the committee, NSF-AST funded midscale activities at a level of $31 million in FY2010, similar to the level at the end of the previous decade. Among the competed programs were the

[4] Jim Ulvestad, National Science Foundation, presentation to the committee on October 8, 2015.
[5] NRC, 2010, *New Worlds, New Horizons*, p. 226.

University Radio Observatories (URO), with a $6 million to $10 million per year budget, the Telescope Systems Instrumentation Program (TSIP), with a $3 million per year budget administered by the National Optical Astronomy Observatory (NOAO), and Renewing Small Telescopes (ReSTAR), a short-term program with a 2009 start and a total budget of $5.4 million. The unsolicited programs ranged from $10 million to $15 million per year for 10 different projects and included the Very Energetic Radiation Imaging Telescope Array System, the Sloan Digital Sky Survey, the Atacama Cosmology Telescope, POLARBEAR, the Hobby-Eberly Telescope Dark Energy Experiment, the Virtual Astronomical Observatory, the Dark Energy Survey, the Murchison Widefield Array, Precision Array to Probe Epoch of Reionization, and LSST design and development.

The NSF-AST Portfolio Review of 2012 recommended a vigorous divestment from many facilities in order to accommodate new priorities, including the Atacama Large Millimeter/submillimeter Array (ALMA) operations, MSIP, and future LSST operations. The Portfolio Review recommended that MSIP include telescope open access time, laboratory astrophysics, MREFC design and development, and long-term mid-scale facilities operations, in addition to the NWNH new telescopes and instruments recommendations. The Portfolio Review also recommended merging the solicited and unsolicited programs into MSIP. While NSF-AST has implemented MSIP, with a first call in 2013 and a second in 2015, it has (consistent with the Portfolio Review recommendation) discontinued the URO, TSIP, and ReSTAR and unsolicited proposal programs. Overall, NSF-AST mid-scale funding *dropped* from $31 million in FY2010 to a nadir of $15.5 million in FY2015, recovering to $21 million in FY2016.

FINDING 3-3: Implementation of the NWNH recommendation of MSIP has been possible only by subsuming previous programs into MSIP and by aggressive divestment from older facilities. The total NSF-AST funding for mid-scale initiatives has dropped by nearly a factor of two since the start of the decade, in stark contrast to the NWNH recommendation of MSIP as a new initiative which would expand opportunities for mid-scale projects.

Following the Portfolio Review, NSF-AST issued a first call for proposals for MSIP in June 2013 and did not separately compete the URO, TSIP, and ReSTAR programs. The identified funding was for 2 fiscal years. Four categories of proposals were accepted: mid-scale science projects, mid-scale facilities, development investments, and open access to telescopes. The maximum request per project was $40 million. NSF-AST received 38 pre-proposals requesting $400 million. Individual project budgets ranged from $3 million to $40 million and were mostly 5-year projects. Twelve full proposals were invited with a total request of $177 million. Six awards were made with a total from NSF-AST FY2014/FY2015 of $27.1 million and other NSF support of $20 million. The awards were as follows: Zwicky Transient Facility ($9 million), Advanced ACTPol ($10 million), HERA ($2.1 million), EHT ($6.5 million), POLARBEAR ($5 million), and NANOGrav ($14.5 million).

Unranked examples of MSIP projects considered promising were identified by NWNH. In the largest funding category, between $40 million and $120 million, were the Big Baryon Oscillation Spectroscopic Survey (BigBOSS), the Frequency Agile Solar Radiotelescope (FASR), the Hydrogen Epoch of Reionization Array (HERA), and the North American Nanohertz Observatory for Gravitational Waves (NanoGrav). In the $12 million to $40 million range were cosmic microwave background (CMB) measurements, Exoplanet Initiatives, Next-Generation Adaptive Optics Systems, and Next-Generation Instruments for Solar Telescopes. Finally, in the $4 million to $12 million group, NWNH mentioned the High-Altitude Water Cherenkov Observatory (HAWC).

HAWC has been built with funds from DOE and the NSF Physics Division (NSF-PHY). BigBOSS is now called the Dark Energy Spectroscopic Instrument (DESI) and is being supported by DOE and NSF-AST. CMB programs at the South Pole are being supported by NSF-Polar, NSF-Physics, DOE, and private funds (South Pole Telescope, Keck, and BICEP). MSIP grants were awarded to HERA, AdvACT (CMB), and POLARBEAR (CMB); and NanoGrav is being funded by NSF-AST-MSIP and NSF-PHY Physics Frontiers Center. Of the mid-scale projects identified by NWNH, FASR, Exoplanet

Initiatives, Next-Generation Adaptive Optics Systems, and Next-Generation Instruments for Solar Telescopes have not yet been funded through MSIP.

FINDING 3-4: Despite limited resources for MSIP, NSF-AST has funded an exciting set of highly ranked proposals in a heavily oversubscribed competition. Some mid-scale programs recommended by NWNH have also moved forward with funding from DOE and from the NSF Physics and Polar Programs. The scientific promise of these projects confirms the NWNH expectation that a mid-scale program would enable major advances that respond nimbly to opportunities on a diverse range of science topics.

GSMT

Participation in one of the U.S. GSMT projects was the third-ranked, ground-based, large-scale priority in NWNH. As stated by NWNH, "[t]hese 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.[6] The report notes that the lower ranking was not due to scientific capabilities but primarily due to concerns about technical readiness and cost and schedule risk. The recommendation called for an "immediate selection by NSF of one of the two U.S.-led GSMT projects" with a goal of a 25 percent share. NWNH noted that "[t]his share could be secured through whatever combination of construction (that is, MREFC), operating funds, and instrumentation support is most favorable."[7]

The two GSMT projects in the United States, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), have made considerable progress in the first half of this decade. Both have passed Preliminary Design Reviews, retiring many of the technical risks identified earlier in the decade. Both have advanced the technology for manufacturing mirrors and mirror segments. GMT is a private consortium consisting primarily of university and research-institute partners. With funding pledged for 70 percent of the budget, the GMT Board recently approved proceeding immediately with construction of its first stage. Site preparation work in Chile is well under way, and ground breaking occurred in November 2015. The first stage consists of four of the seven primary segments, a secondary mirror without adaptive optics capability, and two first-light instruments; when the remaining funding is identified, the project would complete all seven segments and the full first-light suite, including adaptive optics. TMT is a collaboration between the University of California, the California Institute of Technology, and international partners India, China, Japan, and Canada. Similar to GMT, approximately 80 percent of the budget has been pledged by these partners. TMT began construction at its site on Mauna Kea in 2014, but construction has been interrupted until the project can address concerns raised by the Hawaii Supreme Court regarding the permitting process.

Both GSMT projects are actively engaging the optical and infrared (OIR) community through a series of workshops and other outreach activities. The lack of fully identified construction funding, which in turn can partially be traced to the lack of NSF engagement, represents a risk for both programs. If one or both projects are not fully completed, the U.S. public will be left with relatively little GSMT capability, while European astronomers will have the European Extremely Large Telescope.

The highly constrained budget environment has, so far, prevented any significant involvement by NSF in either of the two GSMT projects. NSF did issue a solicitation for planning a partnership model for a GSMT and providing community engagement, to which TMT responded. A preliminary summary of the plan being developed under this award was presented to the committee. It included a scenario for

[6] NRC, 2010, *New Worlds, New Horizons*, p. 228.
[7] NRC, 2010, *New Worlds, New Horizons*, p. 232.

MREFC support of ~20 percent of TMT capital costs beginning at the end of this decade, with operations funding ranging from a similar share to a scenario where the operating costs are fully assumed by other partners. Although the latter would result in a lower allocation of telescope time to the U.S. community, it would still provide a governance role in the project and is an interesting possibility in the current environment where operations funds are highly constrained. The GMT project has also considered public-private partnerships, and the GMT operating agreement is structured to allow flexibility in combinations of capital, operating, and instrumentation funds. NSF participation could come through MSIP instrumentation funding, with allocation of nights to the community, through capital construction support with provision for community access, or though operations support.

FINDING 3-5: The GMT and TMT projects have both made major progress since 2010, and both offer technically feasible routes to achieving the GSMT science goals set forth by NWNH. However, programmatic hurdles remain, and neither project has secured the funding needed to complete construction at its full intended scope. NSF budget constraints have prevented NSF's implementation of the NWNH recommendation that NSF-AST select one partner and participate in GSMT construction.

FINDING 3-6: A selection process leading to MREFC commitment to construction of a U.S.-led GSMT project, without commitment of NSF funds to GSMT facilities operations, would partially address the NWNH recommendation of U.S. federal participation in a GSMT, while retaining flexibility in the NSF-AST budget for implementation of other priorities in the next decade.

With NSF so far unable to meaningfully participate in a GSMT effort, concerns have been raised about broad community access to optical facilities and about the health and balance of the OIR system. The National Research Council report *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*[8] addresses these issues and makes several recommendations for adjusting the system within the limited resources now available. These include an expanded role for NOAO, coordinating exchanges of time between telescopes, organizing workshops to define new instrumentation priorities, and operating the U.S. facilities, particularly in the southern hemisphere, in a coordinated fashion. The report highlights the need for a coordinated system to respond to transient events from new facilities, particularly LSST. Several other recommendations, including development of new instruments and a large share in a GSMT, are challenging to implement in the current environment. In a "Dear Colleague" letter response, NSF highlighted work to respond to these recommendations where practical.[9]

ACTA

ACTA was ranked fourth among ground-based, large-scale activities in NWNH. At that time, U.S. groups had proposed a U.S.-led ACTA effort, named the Advanced Gamma-ray Imaging System (AGIS). NWNH recommended 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"[10] The 2014 Particle Physics Project

[8] NRC, 2015, *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*, The National Academies Press, Washington, D.C.

[9] National Science Foundation, Dear Colleague Letter: NSF/AST Response to the NRC Report "Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System," September 1, 2015.

[10] NRC, 2010, *New Worlds, New Horizons*, p. 24.

Prioritization Panel (P5) recommended to the NSF-PHY and DOE "invest in CTA as part of the small projects portfolio if the critical NSF Astronomy funding can be obtained."[11]

The Čerenkov Telescope Array (CTA) is planned as an open observatory with one array in the northern hemisphere and one in the southern hemisphere. The three leading present-day ground-based gamma-ray efforts (VERITAS (located in Arizona, United States), MAGIC (Canary Islands, Spain), and HESS (Namibia) have largely joined together to form CTA, which is designed to increase the sensitivity to gamma-ray sources by an order of magnitude over a wide range of energies (tens of GeV to above 100 TeV). The main science drivers are the study of high-energy astrophysical particle acceleration in a variety of galactic and extragalactic sources and searches for signals of dark matter interactions. In 2015, the CTA consortium selected its sites: the southern array at European Southern Observatory (ESO), Paranal, Chile, and the northern array at Observatorio del Roque de los Muchachos (ORM), La Palma, Spain. Construction could start as early as 2016, and the U.S. groups would benefit from a timely initiation of U.S. participation. The U.S. groups have developed a plan for participation in CTA, but at a lower level than that originally proposed at the time of NWNH. This plan seeks funding at a level appropriate for the mid-scale programs of the Astronomy and Physics divisions of NSF.

FINDING 3-7: U.S. participation in CTA at budget levels below those recommended by NWNH would still have a significant positive impact on the scientific productivity of the observatory and would give U.S. scientists leadership roles in the CTA program. If the U.S. CTA proposal competes successfully in the MSIP and NSF-Physics mid-scale programs, the NWNH recommendation can be implemented, albeit at a level lower than anticipated in 2010.

THE GROUND-BASED PROGRAM—MEDIUM SCALE

For reference, Table ES.2 of NWNH is reproduced below (Table 3.2). The single priority in this category was the Cerro Chajnantor Atacama Telescope (CCAT, formerly the Cornell-Caltech Atacama Telescope), a submillimeter-wave survey telescope led by a consortium of U.S., Canadian, and German universities.

Despite the high initial priority given to CCAT in NWNH, the project has not secured significant federal funding. CCAT was initially envisioned as a 25-m telescope equipped with large-format cameras to enable surveys at millimeter wavelengths. The planned site for CCAT is at 5,600-meter elevation, some 500 m above the nearby ALMA site. NWNH recommended an NSF-AST investment of $37 million in the $140 million cost of construction of the project, with the remaining funding coming from the university and international partners. NWNH further recommended an annual contribution to operations of $7.5 million from NSF-AST. The NSF contribution so far this decade to CCAT has been support for the design at $4.75 million from 2011 to 2015.

The Portfolio Review reiterated support for an NSF investment in CCAT, but only in the event that MSIP was funded at an annual level of $30 million. Since that goal has not been met, NSF-AST did not support CCAT as a separate line-item and instead encouraged the CCAT consortium to submit a proposal to the MSIP competition, which the consortium did. This proposal, however, was not funded. In the current budget climate, NSF will only contribute to CCAT through future MSIP competitions. The project is now being rebaselined, and a number of international potential partners have expressed interest, including the host country of Chile.

[11] Particle Physics Project Prioritization Panel, 2014, *Building for Discover: Strategic Plan for U.S. Particle Physics in the Global Context*, Department of Energy, Washington, D.C., p. 15,

TABLE 3.2 Medium-Scale, Ground-Based Recommended Activities from the 2010 Astronomy and Astrophysics Decadal Survey

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

[a] The survey's construction-cost appraisal for CCAT is based on CATE analysis and project input, in FY2010 dollars.
[b] The survey's estimates 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 survey's appraisal of operations costs, in FY2010 dollars, is based on project input.
SOURCE: National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., Table ES.2.

FINDING 3-8: In the current budget climate, NSF-AST has not been able to fund CCAT beyond an initial contribution to the design. This is because the NSF-AST budget increases anticipated by NWNH did not materialize, and NSF-AST, consistent with the Portfolio Review's guidance, gave higher priority to funding the MSIP program within the constraints imposed by the budget.

THE GROUND-BASED PROGRAM—SMALL SCALE

For small-scale programs at NSF, NWNH recommended augmentations of $8 million per year (17 percent) to the Astronomy and Astrophysics Research Grants (AAG) program and $5 million per year (50 percent) to the Advanced Technologies and Instrumentation (ATI) program, which are the two primary individual investigator programs in NSF-AST. NWNH additionally recommended DOE and NSF funding of Theoretical and Computational Astrophysics Networks (TCAN) at a level of $1.0 million and $2.5 million per year, respectively. From FY2011 to FY2015, the combined budget of AAG and ATI has instead declined 3 percent, from $58.5 million to $56.6 million in real-year dollars, with a greater drop in purchasing power.[12] The AAG budget in the years between 2012 and 2014 was approximately 10 percent less than it was in 2011, and, although there was an increase in AAG in 2015, it is anticipated that the funding will return to the 2012 to 2014 level in 2016. The ATI budget was further decreased to reallocate funds to MSIP and now stands at a level that is 20 percent below what it was in 2011 and half of what was envisioned in NWNH. NSF funded the TCAN program at $1.5 million per year in FY2014 and FY2015, although there is no TCAN support in the FY2016 budget. DOE did not provide funding for TCAN.

In its list of recommended small-scale activities, NWNH included an augmentation of TSIP to a level of $5 million per year. NWNH recognized that TSIP as a vital component of the OIR system that enabled new instrumentation on privately funded telescope in exchange for community access. As noted

http://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_Interactive_060214.pdf.

[12] Unless otherwise noted, budget numbers in this section are taken from James Ulvestad, Director, Division of Astronomical Sciences, National Science Foundation (NSF-AST), "Responses to Mid-Term Assessment Questions," provided to the committee on December 4, 2015, referred to hereafter as "Ulvestad Responses," p. 8.

previously, TSIP has instead been discontinued as a separate program and subsumed into MSIP, which is, itself, underfunded relative to FY2011 mid-scale programs.

> **FINDING 3-9: Because the NSF-AST budget did not grow at the rate assumed by NWNH, NSF-AST has not implemented the majority of the NWNH recommendations for small-scale projects or for expanded support for individual investigator programs. Support for the individual investigator programs has decreased during the first half of the decade.**

The international (U.S.-managed) Gemini Observatory was an area of concern for the NWNH committee, highlighting community dissatisfaction with the alignment of its capabilities and management to U.S. priorities. NWNH called for a $2 million per year increase in NSF's contribution to the Gemini international partnership to enhance the community's efforts in exoplanets, dark energy, and early-galaxy studies. Language in the FY2011 congressional appropriation led to an increase in the U.S. contribution. With the deployment of the Gemini Planet Imager and plans for a high-resolution optical spectrograph, the instrumentation suite is becoming more capable, and the management structure has been changed to be more responsive to community concerns. Four proposed next-generation Gemini instruments are high-throughput, rapid-response OIR spectrographs similar to those envisioned in the NRC report *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*[13] and well-matched to LSST followup. The greatest change in U.S. access to Gemini came in 2012 with the withdrawal of the United Kingdom from the partnership. This has resulted in the U.S. share of Gemini going from 50 to 65 percent with no increase in the U.S. contribution.

NWNH placed strong emphasis on expanding support for individual investigator grants: "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…. 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."[14]

The success rate of AAG proposals fell from 22.4 percent in FY2010 to a low of 14.8 percent in FY2012, and recovered to 18.0 percent in FY2015.[15] Relative to a decade ago, AAG proposal success rates have fallen by about a factor of two (e.g., the average success rate from FY2000 to FY2005 was 33 percent). While a number of factors contribute to declining proposal success rates,[16] the mismatch between growing scientific opportunities and shrinking available support is ultimately responsible. Feedback can amplify the effect of such a mismatch: as even highly rated proposals are declined for lack of funding, investigators resubmit similar proposals in successive years or to multiple programs, driving proposal pressure up and success rates down. The committee concurs with NWNH that "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."[17] Without adequate support at the level of individual investigators and research groups, the United States cannot reap the rewards of its investment in advanced observational and computational facilities.

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[13] NRC, 2015, *Optimizing the U.S. Ground-Based Optical and Infrared Astronomy System*.

[14] NRC, 2010, *New Worlds, New Horizons*, p. 132.

[15] James Ulvestad, Director, NSF-AST, "NSF Division of Astronomical Sciences (AST) Activities and Plans Pertaining to NWNH," presentation to committee on October 8, 2015, slide 29.

[16] Astronomy and Astrophysics Advisory Committee, 2016, Competed Grant Success Rates in US Astronomy and Astrophysics, National Science Foundation, Arlington, Virginia.

[17] NRC, 2010, *New Worlds, New Horizons*, p. 132.

> **FINDING 3-10: The core grants programs AAG and ATI have declined in real-year dollars and dropped still further in purchasing power over the first half of the decade. This reduction in funding has contributed to a substantial decline in grant funding rates, threatening the scientific productivity of the U.S. ground-based astronomy program.**

THE GROUND-BASED PROGRAM: SUMMARY AND BALANCE ASSESSMENT

As previously noted, NWNH emphasized the importance of a balanced ground-based astronomy program, with a mix of large and medium-scale initiatives and strengthening of core research infrastructure through individual grants and support for instrumentation, technology development, and theory. The combination of an approximately flat NSF-AST budget with rising costs for facility operations has made maintaining such a balance extremely difficult. Averaged over FY2011 to FY2015, the annual NSF-AST budget has been $237 million, equal to its value in FY2011.[18] The annual cost of facilities operations within that budget has risen from $130 million to $146 million over this period because of the ramp up of ALMA operations (from $23 million in FY2011 to $40 million in FY2015) and the beginning of Daniel K. Inouye Solar Telescope (DKIST) operations ($5 million in FY2015), partly offset by $4 million in reduced operations funding for Arecibo and NOAO. With the NSF-AST individual investigator grants program declining 3 percent in real-year dollars over this period, the increases in facilities operations have come at the expense of mid-scale initiatives. As noted previously, when MSIP began in FY2014, it subsumed previous mid-scale support, and the total annual funding for mid-scale projects has declined by a factor of two over the decade. Given the necessity of operating NSF-AST's powerful new facilities and the importance of maintaining support at the individual investigator level, squeezing the mid-scale program was probably the best choice available within a flat budget scenario, but it is opposite to the *augmentation* of mid-scale research funding envisioned by NWNH. Furthermore, the diminished funding of mid-scale programs has the collateral effect of reducing the number of future instrument builders needed for the next generation of cutting-edge initiatives.

> **FINDING 3-11: The combination of a flat NSF-AST budget (in real-year dollars) with new operations costs for ALMA and DKIST, and the need to sustain the individual investigator program, have led to sharp reductions in funding for mid-scale initiatives during the first half of the decade.**

NWNH emphasized the importance of a "vigorous periodic senior review" of facilities to maintain "the appropriate balance in NSF's astronomy and astrophysics research portfolio."[19] It recommended that NSF-AST complete a senior review before mid-decade 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."[20] Responding quickly to this recommendation, NSF carried out its Portfolio Review. The review recommended divestment of several facilities as described above. NSF-AST has moved to implement the Portfolio Review's recommendations, and in several cases, it has been able to implement them by transferring operations to new partners rather than closing facilities. DOE is building DESI for the Mayall telescope and will assume most of the costs of Mayall operations after the

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[18] At the next decimal place, the fiscal year (FY) 2011 to FY2015 average has been $237.2 million in real-year dollars, just above the FY2011 value of $236.8 million, and significantly below the FY2010 value of $246.5 million (James Ulvestad, Director, NSF-AST, "Responses to Mid-Term Assessment Questions," provided to the committee on December 4, 2015.)

[19] NRC, 2010, *New Worlds, New Horizons*, p. 32.

[20] Ibid.

DESI survey begins in 2019. NASA is partnering with NOAO to support development of an extreme radial velocity precision spectrograph for the 3.5-meter Wisconsin/Indiana/Yale/NOAO (WIYN) Telescope and operate exoplanet searches with the NOAO share of WIYN. The NANOGrav consortium (with funding from MSIP and an NSF Physics Frontier Center) and the Breakthrough Listen initiative are supporting Byrd Telescope operations in Green Bank by buying observing time. The committee notes that both arrangements are for finite periods of time and do not preclude the closure of those facilities in the 2020s.

Painful though they are, the divestments recommended by the Portfolio Review are essential to maintaining other key aspects of the NSF-AST program. However, the division's new facilities—ALMA, DKIST, and (at the end of the decade) LSST—are more sophisticated and more complex than the facilities being divested, and they are correspondingly more expensive to operate. Divestment alone will not resolve the budget stresses imposed by rising facilities costs.

Looking ahead, the vigorous, periodic senior review advocated by NWNH may become necessary again in the future. While there are a number of long-lived space missions (e.g., Chandra and Swift), major ground-based facilities have historically remained operational longer than space missions, in part because they can be made continually more powerful with instrumentation that takes advantage of developing technologies and can be repaired more readily. An example of this is the Hubble Space Telescope—its unique long life as the world's leading space observatory is a consequence of the servicing missions that renewed its instrumentation over the span of two decades. Nonetheless, NSF could construct major new astronomical facilities with an identified "prime operations lifetime," and continued operations funding beyond this lifetime could be a *positive* decision informed by the senior review, not a default. The burden of operation costs from MREFC-funded facilities has been recognized as a problem facing other NSF divisions besides AST,[21] and it is likely to grow worse with time as world-class facilities become more expensive.

One important obstacle to closing facilities is the cost of environmental mitigation and returning sites to their pre-construction state. Under the present NSF structure, the costs of facility closeout and environmental mitigation fall to the operating division. It is not hard to imagine circumstances in which closing a facility would impose crippling costs on a division for a large fraction of a decade, and where continued operation could be preferred for financial reasons alone. This problem is also likely to affect NSF divisions other than AST, and finding ways to address it is an NSF-level policy challenge that cannot be resolved by NSF-AST alone.

Unfortunately, the squeeze between rising facility operations costs and a flat NSF-AST budget is on track to become far worse over the next 5-10 years. While projections of out-year facility operations costs are only notional, the estimates presented to the committee by the NSF-AST director suggest increases of about \$10 million in ALMA operations (U.S. share) and \$9 million in DKIST operations between FY2016 and FY2022.[22] Projected NSF operations costs for LSST are estimated at \$7.5 million in FY2021[23] and approximately \$25 million by the time LSST is fully operational in the next decade (Figure 3.1). While full implementation of the Portfolio Review divestment recommendations is an essential step, it will not come close to offsetting this increase in facility operations costs. Unless the NSF-AST budget rises accordingly, there will not be adequate resources to operate the new facilities, even with severe cuts to the individual investigator program and continued restriction of mid-scale funding. Without adequate support for data analysis and theoretical interpretation, many of the discoveries enabled by LSST, DKIST,

[21] Barry C. Barish, NSB Consultant, "The NSF MREFC Program: Perspectives on DUSEL as a proposed MREFC project," presentation to the Committee to Assess the Deep Underground Science and Engineering Laboratory (DUSEL) on December 15, 2010.

[22] FY2016 estimates are based on the FY2016 Budget Request; FY2017 estimates are based on the FY2017 Budget Request; FY2018-FY2022 estimates are based on the FY2017 Budget Request and are notional.

[23] James Ulvestad, Director, NSF-AST, "Responses to Mid-Term Assessment Questions," provided to the committee on December 4, 2015, referred to hereafter as "Ulvestad Responses," p. 4.

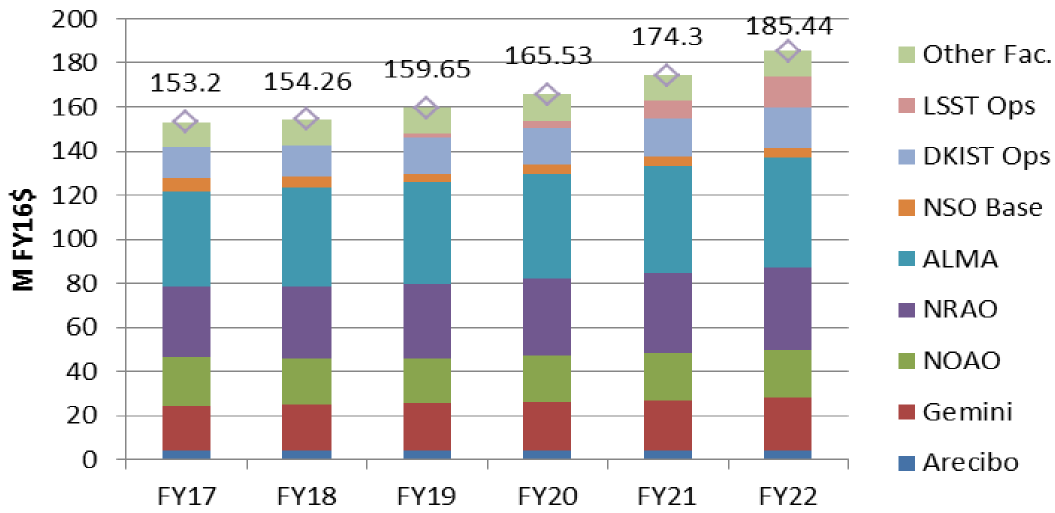

FIGURE 3.1 Anticipated NSF-AST expenditures on facilities in FY2017-FY2022. Data was taken from the President's Budget Request for NSF for FY2017 and are notional. NSO base plus DKIST Operations accounts for the full NSO budget. Arecibo funding given here only includes the NSF-AST contribution to it. Numbers above each vertical bar indicate that entire bar's sum for that fiscal year. Dollar figures are given in FY2016 dollars. NOTE: Acronyms are defined in Appendix C.

ALMA, and other powerful facilities, such as Gemini and the Jansky Very Large Array (formerly the VLA), will be made outside of the U.S. community or with U.S. scientists in supporting rather than leading roles. Conversely, the extraordinary science reach of these facilities, which led to their high-priority rankings in decadal surveys, means that even moderate augmentations in the NSF-AST budget will have highly leveraged science impact.

FINDING 3-12: Even following the divestment recommended by the Portfolio Review, the operations costs of ALMA, DKIST, and LSST will compromise the ability of the U.S. community to reap the scientific return from its premier ground-based facilities. Moderate increases in the NSF-AST budget would have highly leveraged science impact as a consequence of these powerful new facilities.

RECOMMENDATION 3-1: The National Science Foundation (NSF) should proceed with divestment from ground-based facilities which have a lower scientific impact, implementing the recommendations of the NSF Portfolio Review, that is essential to sustaining the scientific vitality of the U.S. ground-based astronomy program as new facilities come into operation.

Even following divestment at the maximum feasible level, anticipated facilities operations costs will constrain the mid-scale and individual investigator programs by an amount that could rise to $10 million to $20 million per year by the end of the decade. The LSST operations cost of $8 million at first, growing to $25 million, will be an additional burden on the AST budget in the first half of the next decade. The committee strongly supports the goal of a balanced program that includes facilities, medium-scale initiatives, and small-scale initiatives. Maintaining this balance is a challenge at the current level of funding.

RECOMMENDATION 3-2: The NSF and the National Science Board should consider actions that would preserve the ability of the astronomical community to fully exploit the Foundation's capital investments in ALMA, DKIST, LSST, and other facilities. Without such action, the community will be unable to do so because at current budget levels the anticipated facilities operations costs are not consistent with the program balance that ensures scientific productivity.

This committee is of the opinion that the optimum allocation of funds between facilities and mid- and small-scale activities is probably different for different levels of funding. Therefore, this balance is best left to the discretion of the NSF-AST Director once budget levels are known, and it would be appropriate for the Director to seek advice from the community by convening a panel for this purpose.

4

Progress Toward NWNH Goals—Space-Based Program

In this chapter, each of the “large,” “medium,” and “small” recommendations in *New Worlds, New Horizons in Astronomy and Astrophysics*[1] (NWNH) are considered, in turn, for the space-based program. As in Chapter 3, the progress that has been made toward the NWNH goals is evaluated, including the programs adopted by the agencies and their plans for the remainder of the decade. Finally, an overview of the space-based program is provided and its balance is considered.

THE SPACE-BASED PROGRAM—LARGE SCALE

For reference, Table ES.5 from NWNH is reproduced below (Table 4.1), listing the priorities for large-scale space-based activities. These included, in rank order, the Wide Field Infrared Survey Telescope (WFIRST), an augmentation to NASA’s Explorer program, the Laser Interferometer Space Antenna (LISA), and the International X-ray Observatory (IXO).

WFIRST

WFIRST was NWNH’s highest-ranked large space initiative, with a science program that incorporated precision measurements of cosmic acceleration from large imaging, spectroscopic, and supernova monitoring surveys, statistical characterization of the demographics of exoplanet systems from a gravitational microlensing survey of the galactic bulge, a large area survey of the galactic plane, and a wide range of galactic and extragalactic investigations enabled by guest investigator studies of the survey data sets and by a Guest Observer (GO) program. The version of WFIRST that has now entered Phase A formulation is significantly different and, in most ways, more powerful than the facility described by NWNH, with a larger aperture telescope, a larger infrared focal plane, and an additional instrument for coronagraphic observations of exoplanets and protoplanetary and zodiacal disks. However, WFIRST as currently designed will not cover as large an area of the sky as envisaged by NWNH, nor is it getting as far into the infrared, due to the heated mirrors. In addition, the telescope will be time-shared between imaging and spectroscopy, which will reduce the amount of spectroscopic survey data obtained. The history of these changes is reviewed below, and the importance of cost control is emphasized, which will be essential to maintain balance in the NASA program as WFIRST proceeds toward launch in the mid-2020s. These remarks are made in the context of strong endorsement of the scientific promise of WFIRST.

[1] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

TABLE 4.1 Large-Scale, Spaced-Based Recommended Activities from the 2010 Astronomy and Astrophysics Decadal Survey

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	Page Reference
1. WFIRST - NASA/DOE collaboration	2020	Dark energy, exoplanets, and infrared survey-science	Medium low	$1.6B	$1.6B	7-17
2. Augmentation to Explorer Program	Ongoing	Enable rapid response to science opportunities; augments current plan by 2 MIDEXs, 2 SMEXs, and 4 MoOs	Low	$463M	$463M	7-19
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	7-20
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	7-21

[a] The survey's cost appraisals for WFIRST, LISA, and IXO are based on CATE analysis and project input, in FY2010 dollars for phase B 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 where different from the total. The U.S. share includes an allowance for extra costs incurred as a result of partnering.
[b] The survey's estimate 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 ESA.
[e] Technical risk assessment of "medium" is contingent on a successful LISA Pathfinder mission.

SOURCE: National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., Table ES.5.

FINDING 4-1: The 2.4-meter telescope, larger infrared detectors, and addition of a coronagraph make the 2016 design of WFIRST an ambitious and powerful facility that will significantly advance the scientific program envisioned by NWNH, from the atmospheres of planets around nearby stars to the physics of the accelerating universe.

Table 4.2 summarizes the changes in WFIRST design from the one described by NWNH to the one approved for Phase A study, including the projected cost of these designs scaled to fiscal year (FY) 2015 dollars. These changes and the cost estimates are discussed in more detail in the following subsections.

History

While not endorsing a specific hardware implementation, NWNH noted that the design of the proposed Joint Dark Energy Mission Omega (JDEM-Omega) satellite, a 1.5-m telescope equipped with large focal plane arrays of H2RG detectors with a 2.0 μm long-wavelength cutoff, had capabilities "essentially identical to those envisaged for WFIRST."[2] Based on the cost and technical evaluation (CATE[3]) of this design, NWNH adopted a cost of $1.6 billion (FY2010 dollars) for WFIRST and emphasized the moderate cost and "medium-low" assessment of its technical risk as important factors in its top ranking.

Following NWNH, NASA established a WFIRST Project Study Office and a Science Definition Team (SDT). The Interim Design Reference Mission (IDRM) adopted a hardware implementation similar to that of JDEM-Omega, but with the substitution of an unobstructed, 1.3-m, off-axis telescope for the 1.5-m on-axis design, providing the same light-gathering power with a smaller primary mirror and cleaner optical path.[4] The Design Reference Mission (DRM1) presented in the SDT's final report[5] differed in two important respects—combining the IDRM's separate imaging and spectroscopic arrays into a single focal plane array with a dispersive element in the filter wheel, and extension of the long-wavelength cutoff to 2.4 μm. By the time this report was completed, the schedule delays and increased cost of the James Webb Space Telescope (JWST) made it clear that a Phase A start for WFIRST would be delayed by several years, and might not happen at all.

Completion of the SDT report[6] coincided with a dramatic new development, the announcement that two 2.4-m optical telescope assemblies (colloquially known as "the NRO telescopes") were being made available to NASA following the discontinuation of the program for which they were originally built. NASA commissioned a new SDT and Project Study Office to examine the feasibility of implementing WFIRST using one of these telescope assemblies (the "Astrophysics Focused Telescope Assets," or AFTA) and to consider the optional addition of an on-axis coronagraphic instrument for direct imaging and spectroscopy of exoplanets. Advances in detector technology also enabled the WFIRST-AFTA SDT to baseline 18 H4RG detectors in place of 36 H2RG detectors, doubling the total pixel count of the wide field instrument. However, the AFTA mirror assembly was designed for operation at ≈ 290 K, degrading the long-wavelength performance relative to earlier WFIRST designs with a colder telescope. The 2013 SDT report[7] proposed an implementation with a 270 K telescope operating temperature and a 2.0 μm long wavelength cutoff, and several options for the coronagraphic instrument. An integral field unit (IFU) was also added. Recognizing the broad range of investigations enabled by the 2.4-meter aperture, this report also recommended an expanded GO program encompassing 25-30 percent of the prime mission, and it recommended that the addition of a coronagraph be accompanied by a 1-year extension of the prime mission (from 5 to 6 years) so that coronagraphic studies could be executed without reducing the length of the dark energy, microlensing, and GO programs.

At NASA's direction, the 2015 SDT report[8] adopted the coronagraph as a (descopable) part of the baseline WFIRST-AFTA mission, rather than an optional addition, and adopted a 6-year prime mission lifetime. The 2015 SDT report, which is the most up-to-date public description of WFIRST-AFTA, introduced a number of refinements based on integrated modeling and coronagraph technology evaluation, but no major changes to the hardware complement. However, partly in response to concerns raised in the 2014 NRC report *Evaluation of the Implementation of WFIRST/AFTA in the Context of New*

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[2] NRC, 2010, *New Worlds, New Horizons*, p. 207.

[3] The CATE, or cost and technical evaluation process, was created by the Astro2010 Survey Committee and a detailed description of the CATE process can be found in the NWNH report.

[4] NASA Goddard Space Flight Center, 2011, *Wide-Field InfraRed Survey Telescope WFIRST Interim Report,* Science Definition Team, http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST_Interim_Report.pdf.

[5] NASA, 2012, *Wide-Field InfraRed Survey Telescope WFIRST Final Report*, Science Definition Team, https://arxiv.org/ftp/arxiv/papers/1208/1208.4012.pdf.

[6] NASA, 2012, *Wide-Field InfraRed Survey Telescope WFIRST Final Report*.

[7] NASA, 2013, *Wide-Field InfraRed Survey Telescope Astrophysics Focused Telescope Assets WFIRST-AFTA Final Report*, Science Definition Team and WFIRST Project, https://arxiv.org/ftp/arxiv/papers/1305/1305.5422.pdf.

[8] NASA, 2015, *Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report*, Science Definition Team and WFIRST Study Office, https://arxiv.org/ftp/arxiv/papers/1503/1503.03757.pdf.

Worlds, New Horizons in Astronomy and Astrophysics,[9] the baseline telescope operating temperature was changed from 270 K to 282 K, and the baseline launch vehicle was changed from an Atlas V to a Delta IV Heavy.

The 2015 SDT report discussed (in its Appendix C) the option of changing from an inclined geosynchronous orbit to an L2 orbit.[10] The principal technical advantage identified for the geosynchronous orbit was the availability of continuous data downlink and thus higher data transmission capability. The most important advantage identified for the L2 orbit was the greater efficiency and flexibility in scheduling microlensing and coronagraph observations—in geosynchronous orbit, microlensing observations of the galactic bulge must be interrupted 4-5 days per month because of Moon observing constraints, and coronagraph observations would typically suffer cutouts of a few hours per day because of Earth observing constraints, depending on target location. Other significant advantages identified for L2 were the substantially lower cosmic ray background (and consequently lower shielding requirement) outside of Earth's trapped electron belt and the greater stability from avoiding variable thermal loading from Earth. This analysis suggested that the advantages of an L2 orbit outweighed the disadvantages, but it also emphasized that "the SDT deliberately avoided writing requirements that could not be met at either location."[11]

Since the completion of the 2015 SDT report, WFIRST has been through one further design cycle, leading to the design presented at the Mission Concept Review in December 2015. The most significant change in this design cycle was to baseline an L2 orbit, with a number of consequent alterations such as addition of data recorders and propellant tanks and a larger antenna for data transmission.

Thanks to (1) JWST remaining on schedule and budget since its 2011 reprogram, (2) the adoption of the 2.4-m National Reconnaissance Office (NRO) telescope, and (3) the addition of the coronagraph, WFIRST-AFTA has enjoyed stronger support in Congress, within NASA, and in the astronomical community, compared to the previous implementations of WFIRST. All three of these developments have played a role in garnering this stronger support, and it is hard to disentangle their individual contributions. In FY2014, FY2015, and FY2016, Congress allocated more funds to WFIRST than requested by the administration. Following the direction of the FY2016 Omnibus Spending Bill, NASA initiated the Phase A start of WFIRST in February 2016. According to presentations to the committee by Paul Hertz, Neil Gehrels, and Kevin Grady, the projected schedule and NASA's Astrophysics Division (NASA-APD) budget enable a 2025 launch of WFIRST, paced by the availability of funding. A steeper funding profile would enable an earlier launch and would reduce the total mission cost, but it might also have a negative impact on program balance in the near term.

In summary, with the necessary funding wedge opened by the approaching ramp-down of JWST construction, NASA is now proceeding with NWNH's top-ranked large space priority, although in a form that is different, and in many ways more powerful, than the one considered by NWNH. The currently anticipated launch date is delayed by approximately 5 years relative to that envisioned by NWNH.

The 2014 National Research Council Report and the Current WFIRST Budget Estimate

The Committee on Assessment of the Astrophysics Focused Telescope Assets (AFTA) Mission Concepts was tasked with assessing the responsiveness of the WFIRST-AFTA DRM, with and without the coronagraph, to the science objectives and strategy of NWNH. This committee finds itself in general agreement with the 2014 report of that committee, *Evaluation of the Implementation of WFIRST/AFTA*,

[9] NRC, 2014, *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.
[10] NASA, 2015, *WFIRST-AFTA 2015 Report*, Appendix C.
[11] NASA, 2015, *WFIRST-AFTA 2015 Report,* p. C-1.

regarding both the promise and the risks of the AFTA implementation of WFIRST and the addition of the coronagraph, although it was not able to review the WFIRST mission in nearly as great detail as the 2014 committee. The committee reiterates and emphasizes the following three findings in *Evaluation of the Implementation of WFIRST/AFTA*:

> **Finding 3-2:** The opportunity to increase the telescope aperture and resolution by employing the 2.4-meter AFTA mirror will significantly enhance the scientific power of the mission, primarily for cosmology and general survey science, and will also positively impact the exoplanet microlensing survey. WFIRST/AFTA's planned observing program is responsive to all the scientific goals described in NWNH. (p. 37)
>
> **Finding 2-4:** The risk of cost growth is significantly higher for WFIRST/AFTA without the coronagraph than for WFIRST/IDRM. (p. 39)
>
> **Finding 3-3:** If implementing WFIRST/AFTA compromises the program balance, then it is inconsistent with the rationale that led to the high-priority ranking in NWNH. (p. 38)

On behalf of the WFIRST Project Office, Neil Gehrels presented to the committee a detailed response to findings in *Evaluation of the Implementation of WFIRST/AFTA*, addressing cost and technical risks, progress in maturation of coronagraph technology, and the role of the coronagraph in the mission.

The projected imaging and spectroscopic depth of WFIRST-AFTA in the 2015 SDT report are lower than those in the 2013 DRM that was assessed in *Evaluation of the Implementation of WFIRST/AFTA*, in part because of an increase in the assumed telescope operating temperature from 270 K to 282 K.[12] Nonetheless, compared to the WFIRST IDRM,[13] the larger aperture and higher pixel count of WFIRST-AFTA make it a substantially more powerful facility for wide field imaging, with larger étendue and higher angular resolution, improving the performance for weak lensing, microlensing, astrometry, and a wide range of potential GO programs. For long wavelength (>1.7 μm) observations and wide field spectroscopy, the gains from aperture and pixel count have been at least partly offset by the increased telescope operating temperature and by the elimination of dedicated spectroscopic focal plane arrays in favor of a single larger array used for both imaging and spectroscopy. For the microlensing science, the yield of detected planets for WFIRST-AFTA is expected to be 2,600 (of which 420 would be three times the Earth's mass or smaller), compared to 1,700 (with 230 small planets) for the IDRM mission, in a smaller allocation of observing time. Even more significantly, the higher spatial resolution and integral field spectrograph mode will significantly increase the number of systems in which the lens star (which hosts the planet) can be directly detected, allowing its spectral type, distance, and perhaps metallicity to be determined.[14]

Evaluation of the Implementation of WFIRST/AFTA recommended an external technical and cost review of WFIRST-AFTA. NASA commissioned Aerospace Corporation to carry out a CATE of the 2015 WFIRST-AFTA DRM, which was completed in February 2015. Informed by this evaluation, NASA projected the cost of this DRM, with the coronagraph, to be $2.0 billion to $2.3 billion in FY2015 dollars.[15] Of this cost, $0.35 billion (in FY2015$) was ascribed to the coronagraph, including the extra year of mission operations, and $0.1 billion was ascribed to support of the expanded GO program recommended by the WFIRST-AFTA SDT.[16] The estimated cost of the "original" WFIRST scope

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[12] NASA, 2015, *WFIRST-AFTA 2015 Report*, Appendix A.

[13] NASA Goddard Space Flight Center, 2011, *WFIRST Interim Report*.

[14] NASA, 2015, *WFIRST-AFTA 2015 Report*.

[15] Paul Hertz, NASA, "NASA Astrophysics: Progress Toward New Worlds, New Horizons," presentation to committee on October 8, 2015.

[16] NWNH explicitly noted that the cost of the guest investigator program was not included in its WFIRST cost estimate.

envisioned by NWNH was $1.8 billion, very close to the NWNH value of $1.6 billion after adjustment from FY2010 to FY2015 dollars, and as stated by P. Hertz, "thereby validates NASA's expectation that the cost of a larger telescope is offset by the savings of using an existing telescope." In other words, the growth in estimated cost between 2010 and 2015 was fully attributable to the combination of the coronagraph, the GO funding, and inflation.

However, changes to the mission design between the 2015 DRM and the version of WFIRST presented at the Mission Concept Review and approved at KDP-A led to an increase of the estimated cost by approximately 25 percent ($550 million).[17] An unknown portion of this change is associated with the change from geosynchronous orbit to L2, and another portion is associated with an increased estimate for the cost of the Delta IV Heavy launch vehicle (the choice of launch vehicle did not change, just its estimated cost). Some of it may simply reflect more accurate assessment as the mission design matures. NASA's current cost projection for WFIRST is $2.6 billion to $2.8 billion in FY2015 dollars for a 2025 launch. A key uncertainty is the launch vehicle cost, which is difficult to project 8-10 years into the future at this time. It is projected that an accelerated funding profile leading to a 2024 launch would save approximately $0.3 billion relative to the "in-guide" profile that leads to a 2025 launch.

Independent of details, and independent of the coronagraph, the risk of cost growth for WFIRST-AFTA remains higher than for the NWNH version of WFIRST. This increased risk arises from the use of inherited hardware, which increases the mass of the telescope system and removes some of the options that would otherwise be available to meet mass or technical margins or to implement cost-saving descopes.

> **FINDING 4-2: Because of the risk of cost growth, the concern raised in *Evaluation of the Implementation of WFIRST/AFTA* that WFIRST could distort the NASA program balance remains a concern. In addition, the delay in the implementation of WFIRST over the schedule anticipated in NWNH means that cost growth in WFIRST would limit options for the next decadal survey.**

The WFIRST Coronagraph

The addition of a coronagraph is a major change to WFIRST not anticipated by NWNH. The WFIRST coronagraph does directly address the highest-priority medium-scale space activity identified by NWNH, a "New Worlds Technology Development Program for a 2020 Decade Mission to Image Habitable Rocky Planets." While the program envisioned by NWNH was laboratory based, the shift to a 2.4-m telescope allows a coronagraph flown on WFIRST to execute a strong science program—imaging and spectroscopy of gas giant and perhaps "super-Earth" planets around nearby stars—in addition to demonstrating starlight suppression technology in space. Simulations of the current coronagraph performance show that the instrument could photometrically or spectroscopically characterize ~16 known giant planets, while a search for new systems would detect and characterize ~12 planets of Neptune size or below, including (if the measured Kepler frequency of planets extends out to 1 AU scales) ~4 super-Earths.[18] The WFIRST coronagraph can also characterize the level of zodiacal light around potential target stars, thus accomplishing one of the essential tasks identified by NWNH as a precursor to a future planet-imaging mission. While ground-based observations are also examining this question, the WFIRST coronagraph measurements will likely be more directly applicable.

> **FINDING 4-3: The WFIRST coronagraph responds to an opportunity that arose after NWNH, the availability of the 2.4-m AFTA telescope. This development allows a space-**

[17] Paul Hertz, NASA, "Astrophysics," presentation to committee February 26, 2016.
[18] NASA, 2015, *WFIRST-AFTA 2015 Report*.

borne coronagraph to carry out an exciting exoplanet science program, in addition to demonstrating technology that would be needed for a future mission capable of imaging Earth-like planets around nearby stars. The addition of the coronagraph, therefore, addresses NWNH's highest medium-scale space-based priority of a New Worlds Technology Development program.

The total cost of exoplanet-related precursor science and technology development, including technology development for the WFIRST coronagraph, significantly exceeds the $100 million to $200 million envisioned by NWNH for the New Worlds Technology Development Program. Given the pressure of budget constraints on realizing the overall scientific program recommended by NWNH, funding any specific program well above the level recommended by NWNH is a concern. However, exoplanet research has progressed significantly since NWNH, and, as evident from the title that the decadal survey committee selected for its report, it is a central scientific focus of NWNH. It is also a science area that resonates strongly with the public and with NASA stakeholders in Congress and the administration. Furthermore, the survey stated that "[i]t 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."[19] Taken together, these developments and the survey's language on the matter justify the currently anticipated expenditure discussed above.

FINDING 4-4: At the currently estimated cost, NASA's decision to add a coronagraph to the AFTA implementation of WFIRST is justifiable within the scientific goals of NWNH. The broader societal interest in the possibility of life beyond Earth is also compelling. However, an increase in cost much beyond the currently estimated $350 million would significantly distort the science priorities set forth by NWNH.

The 2014 NRC report committee found that "introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low technical readiness level (TRL) hardware to flight readiness."[20] It recommended that NASA move aggressively to mature the coronagraph design to a level that would allow credible assessments of its expected scientific performance and its cost and schedule impact on WFIRST. WFIRST support has led to rapid progress on coronagraph technology and performance forecasts, as documented in the 2015 SDT report[21] and in presentations to the committee.[22] In the current WFIRST schedule, the coronagraph is not on the critical path, and recent design modifications make the coronagraph performance relatively insensitive to stability of the telescope optics. The WFIRST Project Team reported that NASA Headquarters has directed that the coronagraph will not impose driving requirements onto the mission design.[23] Nonetheless, as the newest and least technologically mature element of WFIRST, the coronagraph inevitably increases the risk of schedule delays and cost growth.

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[19] NRC, 2010, *New Worlds, New Horizons*, p. 216.
[20] NRC, 2014, *Evaluation of the Implementation of WFIRST/AFTA*, Finding 2-6.
[21] NASA, 2015, *WFIRST-AFTA 2015 Report.*
[22] Scott Gaudi, Ohio State University, "Planetary Systems and Stars," presentation to committee on December 12, 2015; Jeremy Kasdin, Princeton University, "Exoplanet Imaging Technology," presentation to committee on December 13, 2015.
[23] Neil Gehrels, NASA GSFC, "WFIRST Response to Harrison Committee Findings," presentation to the committee on October 14, 2015.

FINDING 4-5: Coronagraph technology has matured rapidly over the past 2 years, addressing one of the key recommendations of the 2014 report *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*. The coronagraph remains a schedule, cost, and technical risk for WFIRST.

The Way Forward

With its 2016 Phase A start, WFIRST is entering a phase of critical design decisions that will affect its capabilities and its cost. The costs associated with funding guest investigators and guest observers are distinct in character from other WFIRST costs because they maintain support for individual investigators and for training of young researchers. The $0.1 billion increase in estimated mission cost associated with WFIRST's expanded Guest Investigator and GO program does not, therefore, tilt the balance of the NASA-APD program in the direction of large projects, despite its association with a large mission. Costs associated with the coronagraph and the sixth year of prime mission operations are likewise in a distinct category, as the scientific rationale for the coronagraph program is distinct from the NWNH rationale for WFIRST. In assessing the alignment of WFIRST with NWNH priorities, it is valuable to distinguish these three cost categories as descopes are considered, since the first category is directly comparable to the NWNH cost estimate, the second was called out in NWNH as expected but not included in their cost estimate, and the third represents new scope for the WFIRST mission.

Many of the decisions during Phase A study will take the form of trade choices in which increased performance can be achieved with increased cost or risk. Also, assessing the value of potential descopes is a substantial part of the project work in Phase A. To remain consistent with the rationale for WFIRST's high ranking in NWNH, trade decisions and scope definitions during Phase A must be made with control of cost and risk as a central consideration. NASA Astrophysics Division Director Paul Hertz discussed with the committee the plans for management, reviews, and cost control during WFIRST formulation and development. In the committee's assessment, these plans maintain a proper emphasis on the importance of cost control in all phases of the project.

A more accurate mission cost assessment will be possible at the end of Phase A, when the mission goals and requirements are fully defined and the mission architecture is more completely understood. After entering Phase B, cost reductions are difficult to achieve because they would typically require changes in scope or requirements. Therefore, Key Decision Point B (marking the entry into Phase B) is a critical time at which to evaluate the WFIRST mission cost estimate and, if necessary, consider changes in mission scope that would maintain the cost and risk at a level that is consistent with the overall program envisioned by NWNH. This action is intended to preserve the scientific priorities of NWNH by enabling Recommendation 4-3 (the Explorer program), Recommendation 4-4 (LISA), and Recommendation 4-5 (Athena), and would preserve a balanced astrophysics program by maintaining support for individual investigator programs (see discussion of a balanced program in Chapter 2).

RECOMMENDATION 4-1: Prior to Key Decision Point B, NASA should commission an independent technical, management, and cost assessment of the Wide-Field Infrared Survey Telescope, including a quantitative assessment of the incremental cost of the coronagraph. If the mission cost estimate exceeds the point at which executing the mission would compromise the scientific priorities and the balanced astrophysics program recommended by the 2010 report *New Worlds, New Horizons in Astronomy and Astrophysics*, then NASA should descope the mission to restore the scientific priorities and program balance by reducing the mission cost.

As previously noted, a faster development schedule would reduce the total mission cost for WFIRST, in addition to advancing its scientific impact. These considerations favor a steeper funding profile if budgets allow it, but it is important not to sacrifice program balance (e.g., Explorer Announcements of Opportunity [AOs] and core research grant programs) within the decade. One strong consideration favoring an accelerated schedule is the desirability of overlap between WFIRST and JWST. As discussed in the 2015 SDT report (Appendix B),[24] the wide field of WFIRST and enormous sensitivity of JWST give the two missions a unique synergy. WFIRST can discover rare objects that are ideal targets for JWST spectroscopic follow-up, such as the brightest $z = 12$ galaxies, pair instability supernova candidates, and the most extreme gravitational lenses. The combination of large-scale context and detailed measurements over small fields is essential for other investigations, such as the study of stellar streams in nearby galaxies.

FINDING 4-6: The unique scientific opportunity afforded by combined WFIRST/JWST observing programs favors development and launch of WFIRST on the earliest schedule that is technically and financially feasible.

As of this writing, there appears to be significant Canadian and Japanese interest in WFIRST participation, with both countries having appointed members to the WFIRST-AFTA SDT. International partnerships could lower the U.S. cost for WFIRST.

U.S. Participation in Euclid

NWNH noted that the science program of the Euclid mission, then in definition phase and competing for an ESA M-Class launch slot, overlapped the dark energy program of WFIRST, using similar techniques but a substantially different hardware implementation and strategy. NWNH noted the possibility of a combined mission, provided that the United States would have a “leading role” and that all of the WFIRST scientific objectives would be addressed. Soon after the completion of NWNH, it became clear that JWST schedule delays and cost increases would severely impact the development schedule of WFIRST as envisioned by NWNH. In this context, the Office of Science and Technology Policy requested an NRC Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey to assess several options for coordinating WFIRST and Euclid, including a plan being negotiated by NASA for a 20 percent U.S. share in Euclid. The panel concluded that a 20 percent U.S. Euclid share would be inconsistent with the recommendations of NWNH because it would not achieve the objectives of WFIRST and would have a significant negative impact on NASA’s ability to implement NWNH priorities.[25]

NASA subsequently requested an NRC Committee on the Assessment of a Plan for U.S. Participation in Euclid to evaluate a proposed U.S. hardware contribution (near-infrared detectors) to Euclid of approximately $20 million. That committee concluded that “the NASA proposal [U.S. participation in Euclid] would represent a valuable first step toward meeting one of the science goals (furthering dark energy research) of NWNH for WFIRST.”[26] It recommended that NASA make a hardware contribution of approximately $20 million “in the context of a strong U.S. commitment to move forward with the full implementation of WFIRST,”[27] and that NASA negotiate with the European Space

[24] NASA, 2015, *Wide-Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets WFIRST-AFTA 2015 Report*, Appendix B.

[25] NRC, 2012, *Report of the Panel on Implementing Recommendations from the New Worlds, New Horizons Decadal Survey*, The National Academies Press, Washington, D.C.

[26] NRC, 2014, *Assessment of a Plan for U.S. Participation in Euclid*, The National Academies Press, Washington, D.C., p. 1.

[27] Ibid.

Agency (ESA) to secure a U.S. position on the Euclid Science Team and inclusion of a team of U.S. scientists in the Euclid Consortium. It also recommended that any hardware contribution exceeding $30 million be subject to an independent community review. The committee also recognized that "additional support for this science team will cost an additional ~$2 million per year for about 10 years, for a total similar to the hardware investment."

At present, NASA has purchased $30 million worth of near-infrared detectors and is also investing approximately $30 million in packaging and testing of these detectors before transfer to ESA. NASA has selected one U.S. Euclid science team comprised of three groups of investigators totaling more than 50 scientists who are now members of the Euclid Consortium, and the principal investigator (PI) of the largest investigator group is a member of the 12-person Euclid Science Team and the Euclid Collaboration Board. NASA has budgeted $17 million of funding for support of these science teams through the 2020 Euclid launch and budgeted further funding for the science team after launch brings the total to $50 million. NASA also plans to fund a U.S. node of the science ground system for $50 million. U.S. scientists making use of archived Euclid data would do so in Guest Investigator mode, but it has not yet been determined how support of those scientists will be structured. Thus, at present the total cost of U.S. participation in Euclid is likely to be in the range of $150 million to $200 million, with the majority of that cost going to support of U.S. science teams and archive activities.[28] This level of participation in Euclid is significantly in excess of the $40 million to $50 million recommended by the NRC Committee on the Assessment of a Plan for U.S. Participation in Euclid.

FINDING 4-7: NASA's investment in Euclid, expected to total between $150 million and $200 million by the end of the mission, is a significant augmentation of the dark energy science program budget beyond the level envisioned by NWNH and by the NRC Committee on the Assessment of a Plan for U.S. Participation in Euclid.

This augmentation has a number of salutary effects. Most importantly, it allows early participation by U.S. scientists in space-based dark energy investigations, and the presence of U.S. investigators on both Euclid and WFIRST science teams enables much better coordination of the two mission's science programs. It will eventually allow joint analyses of data sets to test for systematics and improve statistical constraints. However, this investment necessarily reduces NASA's ability to address other NWNH priorities.

RECOMMENDATION 4-2: In the remainder of the decade, NASA should treat support of Euclid participation beyond the existing commitments to the European Space Agency as lower priority than support of the Explorer program, gravity wave technology development, and X-ray technology development.

Table 4.2 provides a summary of changes to WFIRST, beginning with the JDEM-Omega design described as a template by NWNH. Only the changes that most impact mission architecture or scientific capabilities are listed. From DRM1 to WFIRST-AFTA, pixel count changes from 151 Mpix (0.18″/pixel) to 302 Mpix (0.11″/pixel). Projected costs from 2013 onward include $0.1 billion for a funded GO program. Projected costs from 2015 onward include coronagraph and additional year of prime mission operations. Cost projections are based on combinations of WFIRST Study Office analyses and CATEs performed by Aerospace Corporation.

[28] Input from NASA, March 25, 2016.

TABLE 4.2 Changes to WFIRST Since *New Worlds, New Horizons in Astronomy and Astrophysics*

Reference Mission	Projected Cost (FY2015 dollars)
JDEM-Omega Design—2010	$1.8 billion
1.5 m on-axis telescope	
36 H2RG detectors: 1 imaging array + 2 spectroscopic arrays	
2.0 μm long wavelength cutoff	
L2 orbit, Atlas V launch vehicle	
Interim Design Reference Mission—2011	$1.8 billion
1.5 m on-axis telescope → 1.3m off-axis telescope	
Design Reference Mission 1—2012	$1.8 billion
3 focal plane arrays → 1 larger array with grism in filter wheel	
2.0 μm cutoff → 2.4 μm cutoff	
WFIRST-AFTA 2013 Design Reference Mission—2013	$1.9 billion to $2.1 billion
1.3 m telescope → 2.4 m AFTA telescope (on-axis)	(includes GO)
36 H2RG detectors → 18 H4RG detectors	
2.4 μm cutoff → 2.0 μm cutoff	
Supernova IFU *option* → *baseline*	
GO program increased to 25-30% of observing time	
On-axis coronagraph as an *option* (with 6-year prime mission)	
L2 orbit → inclined GEO orbit	
WFIRST-AFTA 2015 Design Reference Mission—2015[a]	$2.0 billion to $2.3 billion
Coronagraph (with 6-year prime mission) *option* → *baseline*	(includes coronagraph)
Coronagraph development and technology downselect	
2025 launch	
Atlas V launch vehicle → Delta IV Heavy	
WFIRST at KDP-A—2016[b]	
2024 launch	$2.3 billion to $2.5 billion
2025 launch	$2.6 billion to $2.8 billion
Inclined GEO orbit → L2	

[a] Paul Hertz, NASA, "NASA Astrophysics: Progress toward New Worlds, New Horizons," presentation to committee on October 8, 2015.
[b] Paul Hertz, NASA, "Astrophysics," presentation to committee February 26, 2016.

Augmentation to the Explorer Program

The augmentation to the Explorer Program was the second priority among the space-based, large-class priorities in NWNH. The recommendation was to augment the "current plan by 2 Medium-Class Explorer (MIDEX) missions, 2 Small Explorer (SMEX) missions, and 4 Missions of Opportunity (MoO)s."[29] The committee finds the NWNH recommendation for the Explorer program to be ambiguous,

[29] NRC, 2010, *New Worlds, New Horizons*, p.

with reasonable interpretations implying four or six missions (and equal number of MoOs) over the decade. The committee believes that the intent of NWNH was that this recommendation be for an augmentation of four missions during the time period 2012 to 2021, in addition to the two missions that would otherwise have been deployed, for a total of six.[30] The Explorer program augmentation was one of the recommendations that NWNH prioritized even in the eventuality that the NASA budget available for new projects was not as high as NWNH assumed.

Historically, Explorer missions have been remarkably successful in delivering groundbreaking scientific results at moderate cost. Recently completed missions include the Wilkinson Microwave Anisotropy Probe (WMAP), the Galaxy Evolution Explorer, the Rossi X-ray Timing Explorer, and the Wide-Field Infrared Survey Explorer. The Nuclear Spectroscopic Telescope Array (NuSTAR) and Swift are the Explorer missions currently in operation, and they continue to make notable scientific contributions. ASTRO-H (a MoO in collaboration with the Japan Aerospace Exploration Agency [JAXA]) was launched on February 12, 2016. Explorer missions in development are the Neutron-star Interior Composition Explorer (NICER; another MoO to be launched February 2017 to the International Space Station), and the Transiting Exoplanet Survey Satellite (TESS; launch planned for December 2017).

Recognizing that the Explorer program's small- and medium-sized missions "enable rapid response to new discoveries and provide platforms for targeted investigations essential to the breadth of NASA's astrophysics program,"[31] NWNH ranked an augmentation to the Explorer program as its second priority in the category of large space-based projects. In comparison to the Explorer program's original intent of deploying a SMEX or MIDEX every other year, NWNH noted the rate of two per decade represented a significant lost scientific opportunity. Therefore, NWNH recommended that NASA support the selection of "two new astrophysics MIDEX missions, two new astrophysics SMEX missions, and at least four astrophysics MoOs over the coming decade."[32] The recommended augmentation was based on the "high level of scientific return on relatively moderate investment . . . that provides the capability to respond rapidly to new scientific and technical breakthroughs."[33]

NASA's Science Mission Directorate separated the budgeting and selection of the heliospheric and astrophysics Explorer programs to enable implementation of this NWNH recommendation. In September 2014, NASA-APD released the first AO for astrophysics Explorers in this decade (an earlier AO did not proceed to selection). The 2014 AO was for one SMEX and one MoO. The SMEX mission budget was capped at $175 million (FY2015 dollars) (including the cost of access to space, but not including any contributions; NASA-provided launch services may be proposed at a charge of $50 million in FY2015 dollars against the PI-managed mission cost; launch date of selected mission no later than end of 2020). The MoO call was capped at $65 million and suborbital-class missions were capped at $35 million (FY2015 dollars).

As a result of the 2014 AO, three SMEX projects are undergoing Phase A studies for a down-select to one mission expected for summer 2016: IXPE (Imaging X-ray Polarimeter Explorer), PRAXyS (Polarimeter for Relativistic Astrophysical X-ray Sources), and SPHEREx (an all-sky near-infrared spectral survey). In addition, two MoOs are undergoing Phase A studies in response to the same AO issued in 2014, also with a downselect to one MoO planned in summer 2016. These are U.S. participation in JAXA's LiteBIRD cosmic microwave background polarization survey and GUSTO (Gal/Xray U/LDB Spectroscopic Stratospheric Terahertz Observatory).

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[30] Based on input from Roger Blandford, Lynne Hillenbrand, and Marcia Rieke, February 4, 2016.
[31] NRC, 2010, *New Worlds, New Horizons*, p. 208.
[32] NRC, 2010, *New Worlds, New Horizons*, p. 209.
[33] NRC, 2010, *New Worlds, New Horizons*, p. 3.

For the rest of the decade, NASA plans to release a MIDEX AO in FY2016 (but no earlier than September), (including one MoO), another SMEX AO (with one MoO) in 2019, and a MIDEX (with one MoO) in 2021.[34]

Because of budget constraints, NASA's implementation of the augmented Explorer program did not begin as early in the decade as originally planned. The current NASA-APD plan places a high priority on selecting four missions, despite the budget constraints. Even if fully executed, however, the plan does not result in the full augmentation recommended by NWNH.

The committee is concerned that growth in NASA-APD's large programs may prevent even this reduced implementation of the NWNH Explorer program. Therefore, the committee emphasizes the high priority it places on the implementation of the plan with the following recommendation:

> **RECOMMENDATION 4-3: NASA's Astrophysics Division should execute its current plan, as presented to the committee, of at least four Explorer Announcements of Opportunity during the 2012-2021 decade, each with a Mission of Opportunity call, and each followed by mission selection.**

Regrettably, the full augmentation recommended by NWNH may not be executable in the current environment. However, if budgets increase, then restoring the full Explorer augmentation would be consistent with the priorities of NWNH.

LISA

LISA was ranked third among the space-based, large-class priorities in NWNH. The survey described LISA as employing three spacecraft to detect long-wavelength gravitational waves. At the time, LISA was a partnership with ESA, and key technologies remained to be demonstrated, and so the NWNH ranking of LISA was based on an equal partnership between NASA and ESA in the execution of the mission and on the success of the LISA Pathfinder (LPF) mission.

The first half of the decade has brought tremendous progress in gravitational wave astronomy. The first direct detection of gravitational waves by Advanced LIGO (Advanced Laser Interferometry Gravitational-wave Observatory) is a ground-breaking achievement and establishes gravitational wave astronomy at tens of hertz to kilohertz frequencies as a new probe of a wide range of astrophysical phenomena, including black hole growth and evolution, endpoints of stellar evolution, nucleosynthesis of the heaviest elements and nuclear equations of state, and precision tests of general relativity. In the low-frequency regime (10^{-7} to 10^{-9} Hz), the steady accumulation of pulsar timing data, the discovery of many new stable millisecond pulsars, and advancements in instrumentation have improved sensitivity to the point that new upper limits are challenging understanding of the populations of supermassive black hole binaries. The impressive early results from the (LPF mission[35] have demonstrated the key technologies needed for a future space mission to cover the source-rich megahertz portion of the gravitational wave spectrum.

> **FINDING 4-8: The first direct detection of gravitational waves by Advanced LIGO is a ground-breaking achievement that establishes gravitational wave astronomy as a revolutionary new probe of astrophysical phenomena.**

[34] Paul Hertz, NASA, "Astrophysics," presentation to committee February 26, 2016.

[35] M. Armano, H. Audley, G. Auger, J.T. Baird, M. Bassan, P. Binetruy, M. Born, et al., 2016, Sub-femto-*g* free fall for space-based gravitational wave observatories: LISA Pathfinder results, *Physical Review Letters* 116:231101.

Because of the JWST schedule delay and cost increase, and LISA's ranking behind WFIRST in NWNH, it became clear early in the decade that NASA would not have the resources to begin a gravitational wave space mission in the 2010s. Therefore, in 2011 the ESA/NASA co-equal partnership was dissolved. Both NASA and ESA subsequently sponsored studies of possible missions that might meet the scientific goals of LISA as described in NWNH but at significantly less cost. Several concepts were costed by the United States, but none resulted in a mission cost of less than $1.2 billion. The European efforts resulted in the European-led Evolved Laser Interferometer Space Antenna (eLISA) concept with two arms, a reduced arm length and reduced mission time. In the ESA Cosmic Visions competition for large mission launch opportunities, a planetary mission was selected for L1 (the first opportunity). The L2 and L3 launch opportunities were competed as science themes, rather than specific missions, and supported by notional mission architectures. The "Hot and Energetic Universe" (notionally the Athena X-ray mission) theme was selected for the L2 opportunity with launch in the 2020s, and the "Gravitational Universe" (notionally the eLISA mission) theme was selected for the L3 opportunity with launch in the 2030s. The call for mission concepts to address the Gravitational Universe science theme is scheduled for late 2016, with selection in 2017. This call is expected to allow for international contributions of up to 20 percent of the mission cost, with the stipulation that the success of the mission not be compromised by a failure to deliver on the promises made by the international partners. The Chinese and Japanese agencies have expressed interest in participating, as has NASA.

The U.S. groups working on LISA at NASA Goddard Space Flight Center, the Jet Propulsion Laboratory, and in the university community were vastly reduced in size following the 2011 decision by NASA not to proceed with LISA in this decade. During fiscal years 2010 and 2011, the LISA project was funded by NASA at a level of approximately $3 million per year. Since then, the groups have secured only competed funding at a level of about $300,000 per year, with the total for FY2012 to FY2015 (the NWNH timeframe) at $1.3 million.

FINDING 4-9: The dissolution of the U.S. LISA project, and the attendant loss of science and technology funding, has severely impacted preparations for a space gravitational wave mission. If this situation persists, the options for significant U.S. participation in this revolutionary discovery area will be limited.

NASA is currently authorized to plan for U.S. participation in an eLISA mission at the reduced cost of $150 million, which equates to a 10 percent stake in the mission. The current expectation is that some subsystems will be contributed by NASA, and NASA will continue to support a small group of scientists to plan and support the science of eLISA.

In November 2015, LPF was successfully launched, 3 years later than the launch date assumed by NWNH. LPF is now at the Sun-Earth L1 Lagrange point, its intended operating point where gravitational gradients are minimized. LPF tests microNewton thrusters, the inertial control reference system for the proof masses, and picometer interferometry. The mission entered primary science mode at the end of February 2016, and within hours demonstrated disturbance-free flight at residual noise levels that meet or exceed the level-1 science requirements.

The NWNH ranking of LISA was based on an equal partnership between NASA and ESA in the execution of the mission and on the success of LPF. Specifically, NWNH recommended that a decadal survey implementation advisory committee (DSIAC)[36] review the situation mid-decade if LPF "is not a success or if a roughly equal partnership is not possible."[37] While Europe has now taken the lead, the

[36] The DSIAC was envisioned as a standing body to oversee the implementation of NWNH. The Academies' Committee on Astronomy and Astrophysics is currently filling part of this role, while separate, independent study committees of the Academies fill in another part. In practice, the mid-decadal committee is carrying out the mid-decadal assessment that the DSIAC was envisioned to perform.

[37] NRC, 2010, *New Worlds, New Horizons*, p. 19.

opportunity exists for the United States to play a significant role in a gravitational wave mission if the community acts quickly and decisively in the next few years.

> **FINDING 4-10: Results of the LPF mission have demonstrated the feasibility of many of the key technologies needed to carry out a space gravitational wave mission, and ESA has selected a gravitational wave theme for the L3 large mission opportunity. These developments address two of the main conditions identified in NWNH for U.S. participation in a gravitational wave mission.**

The science of LISA is even more compelling than in 2010 with the success of Advanced LIGO in making a direct detection of gravitational waves. NWNH envisioned a major U.S. role in this exciting scientific opportunity. It seems appropriate for NASA and ESA to rethink their strategies—namely, to ensure that the new science enabled by a gravitational wave detector operating at low frequencies, at which some of the most interesting sources are found, is carried out successfully. Steps to reduce mission risk and to improve the scientific return to eLISA are as follows: (1) restore instrumentation for the third arm of the triangle, (2) use a larger rocket delivery system for the required increase in mass, (3) increase the lifetime of the mission, and (4) offer the services of U.S. spaceflight centers for the system engineering and integration of the mission. This would require a significantly larger U.S. contribution than the $150 million technology currently being considered. The newly formed NASA L3 study team would best serve its function by participating in the planning and organization with ESA scientists and by identifying a range of options for U.S. participation in the L3 mission.

> **RECOMMENDATION 4-4: NASA should restore support this decade for gravitational wave research that enables the U.S. community to be a strong technical and scientific partner in the European Space Agency (ESA)-led L3 mission, consistent with LISA's high priority in the 2010 report *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH). One goal of U.S. participation should be the restoration of the full scientific capability of the mission as envisioned by NWNH.**

IXO

IXO was ranked fourth among the space-based, large-class priorities in NWNH. The mission was described as a versatile, large-area, high-spectral resolution X-ray telescope. The X-ray mission IXO addressed many of the high-priority science goals of NWNH, but because of "the technical cost, and programmatic uncertainties associated with the project at the current time,"[38] the mission was ranked fourth by NWNH. Nonetheless, given the importance of the science addressed, NWNH recommended a technology development program with an estimated cost of about $200 million for the 2010 decade. Furthermore, NWNH stated that if IXO were selected as the first L-class mission by ESA, then "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."[39]

As described above, ESA selected the Hot and Energetic Universe science theme for an L2 mission with launch in 2028 and proceeded to develop an IXO-like mission as a European-led project with restrictions on international participation. The resulting mission, named Athena, is a down-scoped, reduced-cost version of IXO. Performance in some key areas has been maintained at near-IXO levels, and in addition, the mission has the capability to perform deep and wide X-ray surveys. Athena is currently in

[38] Ibid.
[39] Ibid.

an early stage of formulation and details of the international partnership (which includes Japan) are being negotiated. An ESA decision to formally start Athena is expected in late 2018 or early 2019.

The Athena design features a large-area X-ray mirror with 2 square meters of collecting area and 5 arcsecond angular resolution. The focal plane has two instruments—a microcalorimeter and a wide field imager. Compared to IXO, Athena lacks X-ray gratings, an X-ray polarimeter, and a hard X-ray instrument. However, the core capability recommended by NWNH for a next-generation X-ray mission is retained. A GO program open to the international community for Athena is also planned, as well as targeted key projects.

Soon after ESA selected the Hot and Energetic Universe science theme, NASA announced its intention to contribute to ESA's mission and is currently planning a contribution of $150 million in hardware. A guiding principle is that a U.S. contribution must enhance the science value of the Athena mission. As of this writing, the exact U.S. contribution has not been finalized, but under discussion are contributions to the microcalorimeter and the wide field imager, consistent with technology development goals for a future U.S.-led X-ray mission.

The Athena capabilities are a compelling subset of those of IXO, and Athena should execute much of the IXO science described by NWNH. Its core capability—high-throughput, high-resolution, spatially resolved X-ray spectroscopy—has been the defining feature of X-ray missions highly ranked in both the 2000 and 2010 U.S. decadal survey reports. NASA technology investments over the past 5 years, and the U.S. contributions to Athena currently under discussion, align well with the NWNH recommendation for the IXO technology investment.

RECOMMENDATION 4-5: NASA should proceed with its current plan to participate in Athena, with primary contributions directed toward enhancing the scientific capabilities of the mission.

The ongoing preliminary mission design for Athena indicates that a descope may be necessary if the total cost is to remain within the €1 billion ESA target. The most likely descope currently discussed involves reducing the mirror effective area, leading to about a 30 percent lower efficiency for most of the science observations envisioned for Athena. The committee believes that the currently planned NASA contribution to Athena is still merited with such a descope. Furthermore, it is possible that an increased level of NASA funding for the Athena mission can prevent a descope and thus significantly increase the amount of science that can be accomplished in the nominal life of Athena. The committee does not recommend a specific action because, as of this writing, the exact nature and the cost of such an increased contribution, which would prevent a descope, are unknown. A future decision on increased U.S. funding for Athena would be inconsistent with NWNH if it distorted the overall balance of the NASA-APD program.

THE SPACE-BASED PROGRAM—MEDIUM SCALE

For reference, Table ES.4 of NWNH is reproduced below (Table 4.3). The ranked recommendations in this category were a New Worlds Technology Development Program and an Inflation Probe Technology Development Program.

TABLE 4.3 Medium-Scale, Space-Based Recommended Activities from the 2010 Astronomy and Astrophysics Decadal Survey

Recommendation	Science	Appraisal of Costs[a]	Page Reference
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	\$100-200M	7-23
2. Inflation Probe Technology Development Program	CMB/inflation technology development and preparation for a possible mission beyond 2020	\$60-200M	7-24

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

SOURCE: National Research Council, 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C., Table ES.4.

New Worlds Technology Development Program

NWNH identified exoplanetary science as one of the fastest-growing and exciting fields of astrophysics. An ultimate goal in this field is to image rocky planets in the "Habitable Zones" of nearby stars and to characterize their atmospheres with spectroscopy. Two key precursor activities were noted. First, the demographics of planetary systems should be measured accurately enough to predict in a statistical sense how common Earth-like planets are around nearby stars. This demographic survey is being realized by Kepler, WFIRST microlensing, and ground-based Doppler measurements. Second, observations are needed to characterize the level of zodiacal light around nearby stars to determine at what level starlight scattered from dust will hamper planet detection. This will be investigated by NASA's investment in the Long Baseline Telescope Interferometer and could be satisfied by WFIRST coronagraphy. Finally, NASA's support of an Extreme Precision Doppler Spectrograph capability helps address a key need identified in NWNH for exoplanet science and precursor investigations in advance of a large exoplanet mission, although not at the full level of precision for velocity measurements recommended by NWNH.

To prepare for a direct-detection mission, NWNH recommended a New Worlds Technology Development Program to advance starlight suppression technology. Funding was envisioned to be at \$4 million per year early in the decade, in addition to generally available technology development funds. In addition, mission development was recommended at an appropriate level for the mission design and scope to be well understood. NWNH envisioned a technology down-select around mid-decade when the design requirements of an imaging mission have become clear. The report recognized that significant funding at a currently uncertain level would be needed for this mission. NWNH recommended that a mid-decadal committee be convened to determine the way forward, including the level of support associated with mission-specific technology development (notionally in the \$100 million to \$200 million range, but at the appropriate level as determined at mid-decade). The NWNH-proposed program was intended to allow a habitable-exoplanet imaging mission to be well formulated in time for consideration by the 2020 decadal survey.[40]

Events played out rather differently than envisioned by NWNH. WFIRST was delayed significantly by JWST, and the mission was redesigned to take advantage of the 2.4-m AFTA mirror. NASA funded technology development in coronagraphy and starshades, as well as probe mission concept studies for both technologies, and a coronagraph augmentation is now included in the WFIRST-AFTA

[40] NRC, 2010, *New Worlds, New Horizons*, pp. 195 and 216.

mission. Selection of an L2 orbit for WFIRST-AFTA would enable the possible addition of a starshade in the future. Following congressional direction, WFIRST began Phase A in February 2016.

The committee reiterates Finding 1-7 from *Evaluation of the Implementation of WFIRST/AFTA*:

> **Finding 1-7:** The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology development program recommended by NWNH by developing and demonstrating advanced coronagraphic starlight suppression techniques in space. (p. 38)

The total investment in NWNH-recommended technology development and precursor science, including expenditures in the first half of the decade and those planned for the second half, includes programs in coronagraph and starshade technology development and in precursor science. In addition, the coronagraph addition on WFIRST-AFTA is a significant investment in exoplanet technology development and science.

> **FINDING 4-11: The current planned decadal investment in NWNH-recommended technology development and precursor science exceeds the level envisioned in NWNH.**

The committee believes that NASA's continued development of coronagraph and starshade technology at a modest level for mission design, scope, and capability is a positive step and that this activity would be profitably evaluated by the next decadal survey. However, given the substantial advances already enabled by WFIRST coronagraph development, the committee assigns higher priority to supporting adequate gravitational wave technology development than to further exoplanet technology development beyond WFIRST.

Inflation Probe Technology Development Program

NWNH's second-ranked, space-based activity in the medium-scale category was a technology development effort (with a view to preparing a mature proposal for a dedicated space mission to study inflation through cosmic microwave background [CMB] observations for consideration by the 2020 decadal survey) contingent on having made a positive B-mode detection from the epoch of inflation. The report also recommended that the NASA Astronomy and Physics Research and Analysis program should augment support for CMB technology development "at a modest level."[41]

A major research goal from the time shortly before NWNH to present has been a search for B-mode polarization as evidence for primeval gravitational waves created during inflation. The strength of the B-mode waves indicates the energy associated with the field causing inflation, and through this connection, the measurement of B-modes has become a strong test of the inflation hypothesis and a possible way to distinguish between models. The measurement of B-mode polarization is much more difficult than measuring the temperature anisotropies. The temperature anisotropies have amplitudes of tens of microkelvin, while B-mode components in an inflation model with tensor-to-scalar ratio of $r \sim 0.1$ would be of order 10 nanokelvin, and the actual level of B-mode polarization might be much smaller. Further difficulties are strong foreground emission and the conversion of E-mode patterns into B-mode patterns by gravitational lensing.

At the time of NWNH, WMAP had made measurements of E-mode polarization patterns associated with the adiabatic density and temperature fluctuations as well as cross-correlation maps between the temperature anisotropy and the polarization. The polarization from both the epoch of recombination at a $z = 1000$ and reionization at $z \sim 6$ was identified, and electron optical depth at these epochs was determined. The lower limit for $r < 0.22$ came from the power exponent of the density

[41] NRC, 2010, *New Worlds, New Horizons*, p. 217.

fluctuations, n_s, which was measured to be less than unity, allowing some contribution from gravitational waves. NWNH stated that, "[t]he convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery…. If these fingerprints of inflation are detected, then a decadal survey implementation advisory committee (DSIAC) … 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."[42] While this has not occurred, significant new results have come from the Planck mission; the WMAP and Planck CMB maps agree, and the cosmological parameters derived from them agree within the errors. The Planck polarization data is consistent with ground-based results from ACTpol, SPTpol, BICEP2/Keck, and POLARBEAR lensing B-modes.

The most recent measurements reflect enormous advances in detector systems. New detector systems consist of arrays of superconducting transition-edge bolometers with associated single-mode frequency filters and polarizers with large formats, including as many as 500 detectors connected by multiplexers to SQUID amplifiers. The sensitivity of the individual detectors of 300 microK $\sqrt{\text{sec}}$ is close to the background limit on the ground.

Measurements from the South Pole as well as from the Atacama site in Chile are continuing. The emphasis is to increase observing sensitivity with even larger formats, to increase the wavelength coverage, and to cover more of the sky. The target is to achieve sensitivity to the gravitational waves that would be present at a tensor-to-scalar ratio of $r \sim 0.01$. Planck results for B-modes are anticipated soon and may also be able to measure or set limits at $r \sim 0.01$. On the ground, a new community-based effort has come together to define the science goals and instrument definition of CMB-S4: a stage IV program to deploy approximately 500,000 detectors spanning 30-300 GHz using multiple telescopes and sites to map $\gtrsim$70 percent of the sky. CMB-S4 was highly ranked by the Department of Energy (DOE)- and National Science Foundation (NSF)-chartered Particle Physics Project Prioritization Panel (P5).

NASA is supporting a near-term plan for higher sensitivity with observations from long-duration balloon flights. To date, several groups have made long-duration balloon flights around the South Pole with polarization sensitive radiometers at multiple wavelengths. It is conceivable that balloon-borne payloads will reach $r \sim 0.001$ with large-format detectors developed for both ballooning observations and a possible space mission by NASA. The ballooning program can also test polarization modulators and space worthy cryogenic systems. In the Explorer program, the MoO (with JAXA) LiteBIRD has been selected for Phase A study, with a downselect expected in summer 2016.

FINDING 4-12: The Inflation Probe Technology Development program is well aligned with the recommendations of NWNH, with NASA, NSF, and DOE supporting technology development and precursor science. Third-generation ground-based efforts and a suborbital program are taking place, targeting CMB B-mode polarization. The proposed CMB-S4 program would push the limits of what can be achieved from the ground and advance understanding of the technology and science requirements for a possible future space mission.

The next decadal survey could consider a larger space mission, which may be the best way to achieve the most sensitive full-sky measurements with good control of systematic errors. In principle, it should be possible to measure the tensor-to-scalar ratio to the level limited only by the ability to remove the foreground contamination. As more information becomes available in the next 5 years, critical design decisions, such as the optimum frequency bands and the best angular scale for the beam, will become clearer.

[42] NRC, 2010, *New Worlds, New Horizons*, p. 198.

THE SPACE-BASED PROGRAM—SMALL SCALE

NWNH identified several areas for augmented support in the small-scale space category, listed in alphabetical (not-ranked) order. The lower-than-expected available budget has meant that some of the recommended augmentations have not occurred. However, some programs have seen increases in excess of those recommended. Assessing which programs have seen increases or decreases is sometimes difficult, due to changes in accounting associated with folding elements of existing programs into new initiatives. In this section, each of the small-scale recommendations from NWNH is addressed in turn.

It was recommended that the Astrophysics Theory Program be augmented by $35 million over the decade. This has not happened, and Astrophysics Theory Program (ATP) funding has remained flat in real-year dollars since 2008. The continued eroding of support in this area threatens the science yield of the current and future mission because modest investments in theory often have very large impact.

An augmentation of $40 million over the decade was recommended for ultraviolet/optical (UV/O) technical development. The actual projected augmentation over the decade is $54 million. The funding increases in this area have been focused on exoplanet-related technologies such as coronagraphs and star shades. It is difficult to disentangle the increases in this area from those coming in response to the medium-scale recommendation for additional support for exoplanet imaging. The committee could not identify funding for non-exoplanet UV/O technical developments as recommended for a future ultraviolet space telescope.

NWNH identified a "mid-technology readiness level (TRL)" gap in support for technology development and recommended that spending on intermediate technology development be increased by $2 million per year early in the decade and $15 million per year by the end of the decade. NASA responded by establishing a new program, the Strategic Astrophysics Technology (SAT), which provided $17 million in FY2015; it is slated to grow to $30 million per year in FY2018. It is difficult to trace how much of this is new funding, because several existing programs were rolled into this one new program.

The $2 million per year augmentation of laboratory astrophysics augmentation has not occurred, and funding in this area is flat or slightly down. However, NASA reports that all proposals rated "excellent" or "excellent/very good" have been funded.

NWNH recommended a $150 million U.S. contribution to the JAXA-led Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission, but noted that a "reduced budget scenario would not permit participation in the JAXA-SPICA mission."[43] SPICA is now being proposed as a joint JAXA/ESA mission for ESA's 2015 M5 AO. U.S. participation may be possible as a MoO in response to the 2016 MIDEX AO.

The Suborbital program was boosted by $7 million per year over FY2011-2012 to a total of $32 million per year in FY2013-2015, broadly in line with the $15 million per year augmentation recommended in NWNH. The augmentation has allowed for the development of ultralong-duration balloon flight capabilities and for an expanded program for mounting suborbital class payloads to the International Space Station. The development of orbital sounding rockets was investigated, but deemed cost prohibitive at this time.

NASA and NSF have established the Theoretical and Computational Astrophysics Networks (TCAN) program in response to the NWNH recommendation. The TCAN program started in FY2014, and was reviewed for continuation in 2015. Implementation has come late in the decade, and at a level significantly below the recommendation. The current NASA contribution is $1.5 million per year, while the recommended level was $5 million per year.

FINDING 4-13: NASA's implementation of NWNH's recommended small-scale activities has been mixed. Some recommended augmentations have not occurred and there have been cuts in some programs recommended for augmentation. Other programs, in particular the

[43] NRC, 2010, *New Worlds, New Horizons*, p. 238.

suborbital and exoplanet areas, have seen increases in excess of what was recommended by NWNH.

THE SPACE-BASED PROGRAM: SUMMARY AND BALANCE ASSESSMENT

As noted earlier, NWNH put a premium on balance in both the ground-based and space-based programs. In the context of NASA, balance is achieved through a diversified portfolio that includes large flagship missions, medium-scale Explorer missions and technology development, and smaller suborbital, data analysis, theory, and laboratory astrophysics programs.

Since FY2011, NASA has reported increased funding in the core research and analysis programs by 22 percent. This category incorporates APRA, ATP, the Exoplanet Research Program (XRP; formerly Origins of Solar Systems), Astrophysics Data Analysis Program (ADAP)/Long Term Space Astrophysics (LTSA), and a modest new investment in the TCAN program at the level of $1.5 million per year. NASA investment in laboratory astrophysics program is included in the APRA component of the budget. Funding for the GO programs has remained relatively flat since FY2011. The launch of JWST is projected to lead to an overall increase in the GO budget toward the end of the decade.

It is instructive to consider, within the core research and analysis programs, those that directly support individual investigators. There are estimates that NASA participation in the U.S. astronomical enterprise provides about two-thirds of the grant funding to individual investigators.[44] Presentations to the committee by Paul Hertz and James Ulvestad reported $145 million in this area supplied by NASA and $75 million by the NSF in FY2015. Thus, any change in NASA's funding profile has a major impact on the astronomical community. Public information provided to the committee shows that NASA's funding for small and medium-sized programs aimed at data analysis and theory, defined here to be the sum of the GO programs (which include the programs for the Explorers, Hubble Space Telescope, and Chandra and international programs such as Herschel and the X-ray Multi-Mirror Mission, as well as the Astrophysics Data Analysis program and ATP) dropped from a high of $107 million in FY2006 to a low of $78 million in 2016. This drop of 26 percent in inflation-adjusted dollars has had a major impact on the support of the community and is likely a major contributor to a sharp drop in proposal success. Most of the drop is due to reductions in the budget for GO programs as existing missions exit prime operations. Budget constraints have implications for the scientific productivity of missions as expressed by the 2014 NASA Senior Review:

> The operation of the nation's space borne observatories is so severely impacted by the current funding climate in Washington that the SRP feels that American pre-eminence in the study of the Universe from space is threatened to the point of irreparable damage if additional funds cannot be found to fill the projected funding gaps.[45]

Likewise, a constant level of funding in the ADAP program has not kept pace with the growth in the volume of archival data available. Dr. Hertz reported to the committee that GO funding will increase later this decade as new missions go into operation.

One of the critical components of the balance in the NASA portfolio is the medium-scale Explorer missions and associated technology development. In response to NWNH, NASA has used the SAT program to support technology development directed at future strategic missions. Specific initiatives have focused on exoplanet, CMB, gravitational wave, and X-ray science, in addition to optics and detector development. Total funding over the first half of the decade has exceeded $64 million. Funding for coronagraph technology development has been included in the overall commitment to WFIRST. Funding for the Suborbital program has also been well supported. As discussed elsewhere in this report,

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[44] NRC, 2000, *Federal Funding of Astronomical Research*, National Academy Press, Washington, D.C.
[45] 2014 NASA Astrophysics Senior Review, Rest of Missions Panel, p.8, Washington, D. C.

however, support for Explorer missions in the first half of the decade has been minimal, although planned AOs between now and the end of the decade would remedy this shortfall.

> **FINDING 4-14: Despite a challenging budget environment, NASA-APD has maintained a balanced portfolio through the first half of the decade and, with the assumption of successful completion of an ambitious Explorer schedule, will do so during the second half of the decade as well. This stability, however, has been preceded by a decline in individual investigator funding during the last part of the previous decade.**

The greatest challenge to maintaining a balanced portfolio is the cost of the JWST and WFIRST missions. The risk of cost growth remains higher for the current WFIRST design than for the NWNH version of WFIRST. For example, the FY2016 congressional appropriation, while providing full support for WFIRST, JWST, Hubble, and SOFIA (Stratospheric Observatory for Infrared Astronomy),[46] has necessitated a $36 million reduction in the rest of the Astrophysics portfolio. As emphasized previously, growth in the cost of WFIRST beyond current estimates could seriously compromise NASA's program balance going forward.

[46] NWNH recommended that SOFIA participate in the senior review process to evaluate its role in NASA's portfolio.

5

The Next Decadal Survey of Astronomy and Astrophysics

By assembling the community to determine its scientific priorities every decade, making the hard choices in advance of the associated political and budgetary processes, and arriving at an informed consensus on the best and most executable scientific programs, the astronomy and astrophysics decadal survey, conducted by the National Academies of Sciences, Engineering, and Medicine, provides guidance to Congress and the Administration on scientific goals. In particular, NASA's Astrophysics Division and the NSF's Division of Astronomical Sciences (NSF-AST) have for decades been guided by its contents, and in recent years, the Department of Energy (DOE) has begun to look to the survey to see where the discipline is headed. Astronomy was the first discipline to organize such a decadal survey. Other scientific disciplines have followed suit, and the Academies' decadal process is becoming established as a critical component of planning for several fields.[1]

However, the evolution of both the science and the budgetary landscape requires that the decadal process itself be reviewed periodically to derive lessons learned and best practices that are aimed at ensuring that future decadal-ranked missions and initiatives are aligned with realistic budgetary expectations, and to ensure that the advice given by the decadal process is informed and credible. Identifying best practices, emerging issues, and current activities that can help prepare for the next astronomy and astrophysics decadal survey, due to be completed in 2020, is not only prudent, but necessary at this time, if the United States is to harvest the rich scientific promise of this bountiful age of astronomy (see the Academies' report *The Space Science Decadal Surveys: Lessons Learned and Best Practices*[2]).

The committee's statement of task states that the committee "may provide guidance on … potential activities in preparation for the next decadal survey." As such, the committee provides discussion of the next decadal survey of astronomy and astrophysics as a resource for the organizational efforts going into the next survey.

THE COST AND TECHNICAL EVALUATION PROCESS, LIFECYCLE COSTS, AND DECISION RULES

The Cost and Technical Evaluation (CATE) Process

New Worlds, New Horizons in Astronomy and Astrophysics[3] (NWNH) was the first of the space science decadal surveys to implement independent cost and technical evaluations (CATEs) for all major projects being considered for prioritization, both ground- and space-based. This development in the

[1] There have been decadal surveys for each of heliophysics, Earth science, planetary science, the various subdisciplines of physics, ocean science, and civil aeronautics.

[2] National Academies of Sciences, Engineering, and Medicine (NASEM), 2015, *The Space Science Decadal Surveys: Lessons Learned and Best Practices*, The National Academies Press, Washington, D.C.

[3] National Research Council (NRC), 2010, *New Worlds, New Horizons in Astronomy and Astrophysics*, The National Academies Press, Washington, D.C.

decadal process was implemented in response to the 2008 NASA Authorization Act, which directed that the decadal survey process "shall include independent estimates of the life cycle costs and technical readiness of missions assessed in the decadal surveys whenever possible."[4] The CATE process was developed for the decadal surveys in order to provide an independent, standardized process to produce a figure-of-merit for technical and cost risk that aids in the decadal surveys' science prioritization. CATE, as implemented by the Aerospace Corporation in partnership with the Academies, is based on historical and continuously updated and validated databases and methods. It is designed to evaluate diverse mission concepts of varying design maturity. The CATE methodology incorporates cost growth based on the historical record and the state of the design or development. CATE assesses the technical risk and readiness and then monetizes the technical risks into potential design growth and associated cost and schedule threats. The objective of the CATE process is to perform a cost and technical risk analysis for a set of concepts that may have a broad range of maturity and to assure that the analysis is consistent, fair, and informed by historical data.

This committee believes that the overall impact of the CATE process was positive, although not without some shortcomings. One shortcoming arose because Aerospace Corporation, which performed the CATEs under contract with the Academies, had less experience with ground-based projects than with space missions. Another shortcoming was that CATE is not a full and detailed costing exercise and should not be considered as such. Rather, it is an attempt to carry out an analysis of cost and technical risk for each major mission being considered for high-priority ranking—an analysis that is on an equal footing on a mission-by-mission basis so as to enable relative comparison within an approximate overall budget envelope. The committee supports the lessons learned and best practices provided in *Space Science Decadal Surveys.*[5]

In addition, this committee concurs there may be merit in introducing additional flexibility into the CATE process—for instance, by allowing a larger subset of promising initiatives that emerge from it and the decadal survey, but are not top-ranked by virtue of cost and technical risk concerns, preliminary funding to retire some of the risk identified therein. Furthermore, a two-step process might be useful, as advocated in *Space Science Decadal Surveys*, which begins with a preliminary CATE of a large subset of initiatives, which would be followed by the more detailed CATE of the smaller subset that emerges as the most viable among this first group. Finally, some of the initiatives evaluated in NWNH perceived that there was insufficient opportunity to correct misconceptions that led to inaccurate cost estimates. Therefore, some means to provide feedback during future CATE processes might be explored, while recognizing that the appropriately confidential deliberative process of Academies committees, including decadal survey committees and panels, is an important tool in ensuring the independence of the advice the decadal survey reports provide. Nevertheless, the overall impact of the CATE process was positive, allowing a fair and objectively informed approach to prioritization within a defined budget envelope. An independent CATE process, in whatever future form, is essential for the credibility of cost estimates used by the decadal survey committee, as well as for the credibility of the decadal process itself. Cost and technical evaluations played a crucial role in NWNH. Modest, early investment in developing future concepts and assessing their costs greatly facilitates the overall decadal process.

Life-cycle Costs

As already emphasized in this report, facilities operations costs in NSF-AST have a major impact on resources for new medium and small initiatives. Without an augmentation in its overall funding level, the anticipated growth of operations costs at NSF-AST is likely to severely compromise the grants

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[4] National Aeronautics and Space Administration Authorization Act of 2008, P.L. 110-422, Section 1104 (October 15, 2008).

[5] See NASEM, 2015, *Space Science Decadal Surveys*, pp. 6 and 52-53 and Appendix B.

program and the new Mid-scale Innovations Program (MSIP), making effective use of the new facilities difficult, to the long-term detriment of U.S. astronomy. Currently, operations for facilities constructed using MREFC funds come out of NSF-AST funds. NWNH considered the potential impact of operations costs. Continuing in this tradition, future decadal surveys would have enhanced effectiveness if consideration of the life-cycle cost—including design and development, construction, operations, pipeline data processing, and data curating—of a "prime mission" with a well-defined lifetime were included in the deliberations that lead to prioritization of ground-based activities. This approach is already the norm for space-based activities and facilitates long-term planning.

NASA has initiated studies of several selected large- and "probe"-class mission concepts to prepare the concepts for detailed consideration by the next decadal survey. The large mission-class studies are receiving funding support from NASA. It is hoped that such modest investments will mature these mission concept designs so that the next survey committee will have a fuller understanding than in past surveys of the necessary effort to implement any particular one. NASA should be commended for inaugurating these concept studies.

Decision Rules

NWNH attempted to provide various off-ramps and decision points in the event of changes in the budget landscape. It was the first decadal survey in space science that was tasked with assembling these so-called decision rules. However, the additional constraints on both the NASA and NSF budgets that subsequently emerged have made the survey's full implementation impossible. Strategic advice is most useful if it is robust in the likely case that the actual budgets differ substantially from the assumed budgets in the decadal process. Future surveys could incorporate guidance to the government on how to reprioritize when budgets are significantly different from assumptions. *Space Science Decadal Surveys* provides useful lessons in this regard.[6]

NWNH recommended that an independent advisory committee be created to assist with federal planning in astronomy and astrophysics.

> 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.[7]

In addition to these annual reports, throughout NWNH the DSIAC was charged to provide guidance to the agencies at numerous decision points if or when those points were reached.

The DSIAC as envisioned by NWNH did not fully come to fruition; however, its work has been partially carried out in a piecemeal fashion by the cumulative efforts of the Academies' standing Committee on Astronomy and Astrophysics (CAA) and the several, independent Academies report-writing committees that have been chartered since 2010. Since the CAA as it is currently manifested is not charged by the agencies to provide periodic (annual) reports, this part of NWNH's recommendation with respect to the DSIAC has not been fulfilled. The next decadal survey will likely again consider the astronomy and astrophysics advisory structure.

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[6] NASEM, 2015, *Space Science Decadal Surveys*, p. 65.
[7] NRC, 2010, *New Worlds, New Horizons*, p. 15.

STRUCTURE AND ORGANIZATION OF THE SURVEY PROCESS

In the 2010 NWNH process, the decadal survey committee received information generated by five Science Frontier Panels (SFPs) and four Project Prioritization Panels (PPPs). The SFPs were charged with studying the white paper input from the research community on the science drivers in their fields and identifying the most promising opportunities for progress in the next decade in the form of a set of high-priority questions and areas of discovery. The PPPs then used the SFPs output and conducted in-depth studies of the technical and programmatic issues related to scores of potential research activities identified by the community in a heavily subscribed request for information (RFI) process. The PPPs also engaged with the Aerospace Corporation on the CATE process and carried out an initial draft ranking of research activities in their respective portfolios. The survey committee then examined and assimilated the reports of these panels as they determined their single, comprehensive program. There are pluses and minuses to this structure, and this organizational approach was a departure from the past. The SFP/PPP model ensured a thorough vetting of the options and was a major method through which the broader astronomy community was involved in the decadal process. However, this process also proved more complex and time-consuming than previous surveys. In particular, the SFPs and PPPs produced separate reports, which themselves were independently reviewed and published, and these did not always align with the survey committee's final conclusions. Reconsideration of this practice may be warranted when planning future surveys. In addition, the survey committee of NWNH was larger than in the past (with 23 members). When the next survey is constituted, thought might be given to committee size and nimbleness, while ensuring the necessary collective expertise and breadth of viewpoints.

During the decade preceding a survey, there are multiple independent white papers and federal advisory committee reports that collectively, and in a comprehensive fashion, identify progress made to date, promising new science directions, the hottest areas of astronomy, and the technical methods to address them. This considerable effort can be assembled, summarized, and then channeled into the decadal process itself. As a part of the next decadal process, the Academies can again assemble and summarize prior relevant advisory committee and Academies reports. This systematically assembled archive will help streamline the 2020 effort, obviate the need to perform redundant studies during the survey, and provide useful traceability.

PLANNING FOR THE NEXT DECADAL SURVEY

The State of the Profession

NWNH made a comprehensive effort to survey the state of the profession and workforce issues through its six Infrastructure Study Groups (ISGs). While the information collected by the ISGs was not able to be made publicly available, it was critical to the survey committee's deliberations on these issues.[8] Given the increasing focus on diversity, alternate career paths, and pipeline issues in science in general, and in astronomy in particular, a future decadal survey would be of additional value to its stakeholders if it could address these topics in more detail. Therefore, the committee concludes that incorporating a detailed assessment of the health of the astronomy profession—its diversity, the effects of major funding issues, and pipeline issues, among other items—could be useful for the next survey and executed during the survey process or prior to it.

[8] The ISGs were not formally chartered Academies committees, as the SFPs and PPPs were, so they could not produce public reports.

Public and Private Support for Astronomy vis-à-vis the Decadal Survey

The public/private partnership in astronomy the United States has in the past hundred years been a strength of U.S. astronomy. However, given the recent difficulties encountered by the Thirty Meter Telescope and Giant Magellan Telescope projects, the cancelling of the Telescope Systems Instrumentation Program, lack of a plan for NSF participation in future optical 30-meter telescope planning and construction, and the disconnect between the public decadal process and private deliberations and funding, it may be time to consider developing a process for a unified effort between the public and private spheres in an attempt to optimize the U.S. astronomical enterprise as a whole. Therefore, the committee believes that engaging from the outset the private sector of U.S. astronomy, as well as private philanthropies, in the upcoming survey process could be helpful to the eventual outcome of the 2020 decadal process.

International Coordination and Participation

Space Science Decadal Surveys identified a number of useful best practices to encourage better incorporation of international perspectives and processes into the U.S. decadal survey process.[9] Many space missions and ground-based efforts (e.g., the Atacama Large Millimeter Array and the Extremely Large Telescopes) are joint international efforts and must be coordinated, and there are many examples of successful joint international missions. However, recent experience with the International X-ray Observatory and the Laser Interferometer Space Antenna bears mentioning. Although NWNH ranked them both highly, there was not sufficient funding available for NASA to pursue these mission concepts in addition to higher-priority activities. What were previously strong ties between the United States and Europe weakened as a result, and Europe soon established its own efforts while preserving the possibility of a minority role for the United States. With the emergence of Europe, Japan, Canada, Russia, and (soon, possibly) China and India as major players in space astrophysics, a stronger and more creative effort might be made to engage potential international partners in the decadal survey process, as reflected in *Space Science Decadal Surveys*. The mismatch of the various funding cycles is a major challenge, but the international nature of the science would seem to demand greater effort at the decadal level concerning international coordination and expectations.

Engagement with the U.S. Community

In the run-up to a decadal survey, there can be a mismatch between the expectations and hopes of the astronomy community and known (or at least expected) budget limitations and mission plans. Incorporating budget projections into a future decadal survey, such as was done in NWNH, will be essential to achieving federal buy-in and support for its recommendations. Communicating these budget expectations under which a credible survey must work to the entire U.S. astronomy community in advance of the 2020 survey is therefore also essential, so that the community has the opportunity to prepare activities within that context if it so chooses. The American Astronomical Society, the Academies, and the federal agencies are in the best position to perform this function.

[9] NASEM, 2015, *Space Science Decadal Surveys,* pp. 43 and 53.

Appendixes

A

Statement of Task

The National Research Council shall convene an ad hoc committee of 12-15 members to review the responses of NASA's Astrophysics program, NSF's Astronomy program, and DOE's Cosmic Frontiers program (hereafter the Agencies' programs) to previous NRC advice, primarily the 2010 NRC decadal survey, "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH).

In the context of funding circumstances that are substantially below those assumed in NWNH, the committee's review will include the following tasks:

1. Describe the most significant scientific discoveries, technical advances, and relevant programmatic changes in astronomy and astrophysics over the years since the publication of the decadal survey;
2. Assess how well the Agencies' programs address the strategies, goals, and priorities outlined in the 2010 decadal survey and other relevant NRC reports;
3. Assess the progress toward realizing these strategies, goals, and priorities; and
4. In the context of strategic advice provided for the Agencies' programs by Federal Advisory Committees, and in the context of mid-decade contingencies described in the decadal survey, recommend any actions that could be taken to maximize the science return of the Agencies' programs.

The review should not revisit or alter the scientific priorities or mission recommendations provided in the decadal survey and related NRC reports but may provide guidance on implementation of the recommended science and activities portfolio and on other potential activities in preparation for the next decadal survey.

B

Letter of Request

National Aeronautics and Space Administration
Headquarters
Washington, DC 20546-0001

NOV 20 2014

Reply to Attn of: SMD/Astrophysics Division

Dr. David Spergel
Chair, Space Studies Board
National Research Council
500 5th Street NW
Washington, DC 20001

Dear Dr. Spergel,

The NASA Authorization Act of 2005 establishes a requirement for rolling annual assessments of NASA's science programs. The two principal components of this oversight requirement are National Academy of Sciences (NAS) reviews and NASA Administrator reports to the House Committee on Science, Space, and Technology and to the Senate Committee on Commerce, Science, and Transportation on findings of these and other timely reviews of the programs in question and on planned actions to be taken in response to these reviews. It has been NASA's practice to phase these reports and the underlying NASA assessments in the order in which the most recent Academy science program decadal surveys have been delivered to NASA.

The first reviews and reports in this series have been completed for all four of NASA's science disciplines, astrophysics, planetary science, heliophysics, and Earth science. The next field of science to be reviewed is Astronomy and Astrophysics. The primary recommendations against which NASA's performance should be evaluated are those provided in the NAS decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics* (2010). It is anticipated that this review will be co-sponsored by the co-sponsors of the 2010 decadal survey, the National Science Foundation (NSF) and the Department of Energy (DOE).

In order to support development of NASA's report to the Committee, I request that the NAS convene an ad hoc committee to review the responses of NASA's Astrophysics program, NSF's Astronomy program, and DOE's Cosmic Frontiers program (hereafter the Agencies' programs) to previous NRC advice, primarily the 2010 NRC decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH).

Given the funding circumstances that are substantially below those assumed in NWNH, the committee's review will describe:

The most significant scientific discoveries, technical advances, and relevant programmatic changes in astronomy and astrophysics over the five years since the publication of the decadal survey;

- How well the Agencies' programs address the strategies, goals, and priorities outlined in the 2010 decadal survey and other relevant NRC reports;
- Progress toward realizing these strategies, goals, and priorities; and
- In the context of strategic advice provided for the Agencies' programs by other Federal Advisory Committees, and in the context of any mid-decade contingencies described in the decadal survey, any actions that could be taken to maximize the science return of the Agencies' programs.

The review should not revisit or alter the scientific priorities or mission recommendations provided in the decadal survey and related NRC reports, but may provide guidance about implementation of the recommended science and mission portfolio and about other potential activities in preparation for the next decadal survey.

In order for NASA to be able to use the results of the Astrophysics review in formulating its programs and requirements, the Academy's findings must be received by NASA no later than April 1, 2016.

I request that the NRC submit a plan for execution of the proposed performance review by the Space Studies Board. Once agreement on the scope, cost, and schedule of the proposed study has been achieved, the contracting officer will issue a task order for implementation. The point of contact within the Science Mission Directorate will be Dr. Paul Hertz, who can be reached at (202) 358-2150 or paul.hertz@nasa.gov.

Sincerely,

John M. Grunsfeld
Associate Administrator for
Science Mission Directorate

cc: National Science Foundation/Fleming Crim
- James Ulvestad

Department of Energy/James Siegrist
- Kathy Turner

Massachusetts Institute of Technology/Paul Schechter
University of Arizona/Marcia Rieke
National Research Council/David Lang
- Michael Moloney
- James Lancaster

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C

Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
AAG	Astronomy and Astrophysics Research Grant
AAS	American Astronomical Society
ACT	Atacama Cosmology Telescope
ACTA	Atmospheric Čerenkov Telescope Array
ACTpol	Atacama Cosmology Telescope polarization sensitive receiver
ADAP	Astrophysics Data Analysis Program
ADMX	Axion Dark Matter Experiment
ADP	Astrophysics Data Analysis program
AdvACT	Advanced Atacama Cosmology Telescope
AFTA	Astrophysics Focused Telescope Assets
AGILE	Astro-Rivelatore Gamma a Immagini Leggero
AGIS	Advanced Gamma ray Imaging System
AIP	American Institute of Physics
aLIGO	advanced Laser Interferometer Gravitational-Wave Observatory
ALMA	Atacama Large Millimeter Array
AMS	Alpha Magnetic Spectrometer
ANITA	Australian National Institute for Theoretical Astrophysics
AO	Announcement of Opportunity
APOGEE	Apache Point Observatory Galactic Evolution Experiment
APRA	Astronomy and Physics Research and Analysis
APS	Astrophysical and Planetary Sciences
ARA	Askaryan Radio Array
ARIANNA	Antarctic Ross Iceshelf Antenna Neutrino Array
ART-XC	Astronomical Roentgen Telescope X-ray Concentrator
ASAS-SN	All Sky Automated Survey for Supernovae
ATA	Allen Telescope Array
ATI	Advanced Technologies and Instrumentation
ATP	Astrophysics Theory Program
AU	Astronomical Unit
AUI	Associated Universites, Inc.
BAO	baryon acoustic oscillation
BICEP	Background Imaging of Cosmic Extragalactic Polarization
BigBOSS	Big Baryon Oscillation Spectroscopic Survey
BOSS	Baryon Oscillation Spectroscopic Survey
CAA	Committee on Astronomy and Astrophysics
CALET	CALorimetric Electron Telescope
CARMA	Combined Array for Research in Millimeter-wave Astronomy

CASS	Cranfield Astrobiological Stratospheric Sampling
CATE	Cost and Technical Evaluation
CCAT	Cerro Chajnantor Atacama Telescope
CLASH	Cluster Lensing And Supernova survey with Hubble
CMB	Cosmic microwave background
CSO	Caltech Submillimeter Observatory
CTA	Cerenkov Telescope Array
D&D	Design and Development
DES	Dark Energy Survey
DESI	Dark Energy Spectroscopic Instrument
DKIST	Daniel K. Inouye Solar Telescope
DLR	German Aerospace Center
DOE	Department of Energy
DRM	Design Reference Mission
DSIAC	Decadal Survey Implementation Advisory Committee
E	Excellent
EBEX	E and B Experiment
eBOSS	Extended Baryon Oscillation Spectroscopic Survey
E-ELT	European Extremely Large Telescope
EHT	Event Horizon Telescope
eLISA	Evolved Laser Interferometer Space Antenna
ELT	Extremely Large Telescope
ESA	European Space Agency
ESO	European Southern Observatory
E/VG	Excellent/Very Good
FASR	Frequency Agile Solar Radiotelescope
FAST	Fast Auroral Snapshot Explorer
GBT	Green Bank Telescope
GMT	Giant Magellan Telescope
GO	Guest Observer
GSFC	Goddard Space Flight Center
GSMT	Giant Segmented Mirror Telescope
GUSTO	Gal/Xray U/LDB Spectroscopic Stratospheric Terahertz Observatory
HAWC	High-Altitude Water Cherenkov Observatory
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel
HERA	Hydrogen Epoch of Reionization Array
HESS	High Energy Stereoscopic System
HETDEX	Hobby-Eberly Telescope Dark Energy Experiment
HSC	Subaru Hyper-Suprime Camera
HST	Hubble Space Telescope
IDRM	Interim Design Reference Mission
IFU	integral field unit
IPEX	Imaging X-ray Polarimeter Explorer
IPTD	Inflation Probe Technology Development

IR	Infrared
ISG	Infrastructure Study Group
ISS	International Space Station
ISS-CREAM	ISS-Cosmic Ray Energetics and Mass
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JDEM-Omega	Joint Dark Energy Mission Omega
JPL	Jet Propulsion Laboratory
JUICE	JUpiter ICy moons Explorer
JVLA	Jansky Very Large Array (formerly the VLA)
JWST	James Webb Space Telescope
KAGRA	Kamioka Gravitational Wave Detector
KDP-A	Key Decision Point A
KPNO	Kitt Peak National Observatory
LHC	Large Hadron Collider
LIGO	Advanced Laser Interferometry Gravitational-wave Observatory
LISA	Laser Interferometer Space Antenna
LiteBIRD	Light [Lite] satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection
LPF	LISA Pathfinder
LSST	Large Synoptic Survey Telescope
LTSA	Long Term Space Astrophysics
LUX-ZEPLIN	Large Underground Xenon-ZonEd Proportional scintillation in LIquid Noble gases
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Observatory
MIDEX	Medium-Class Explorer
MoO	Mission of Opportunity
MREFC	Major Research Equipment and Facilities Construction
MSFC	Marshall Space Flight Center
MSIP	Mid-Scale Innovations Program
MWA	Murchison Widefield Array
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
NASA	National Aeronautics and Space Administration
NASA-APD	NASA Astrophysics Division
NICER	Neutron-star Interior Composition Explorer
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRO	National Reconnaissance Office
NSF	National Science Foundation
NSF-AST	NSF Division of Astronomical Sciences
NSF-PHY	NSF Division of Physics
NuSTAR	Nuclear Spectroscopic Telescope Array
NWNH	*New Worlds, New Horizons*
NWTD	New Worlds Technology Development

OIR	Optical and Infrared Astronomy
ORM	Roque de los Muchachos Observatory
OSS	Origins of Solar Systems
P5	Particle Physics Project Prioritization Panel
PAG	Particle Astrophysics and Gravitation
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PAMELA	Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics
PAPER	Precision Array to Probe Epoch of Reionization
PFC	Physics Frontiers Center (NSF)
PIPER	Primordial Inflation Polarization Explorer
PPP	Project Prioritization Panels
PR	Portfolio Review
PRAXyS	Polarimeter for Relativistic Astrophysical X-ray Sources
PTF	Palomar Transient Factory
ReSTAR	Renewing Small Telescopes
RFI	Request for Information
SAT	Strategic Astrophysics Technology
SDSS	Sloan Digital Sky Survey
SDT	Science Definition Team
SFP	Science Frontier Panel
SKA	Square Kilometer Array
SMEX	Small Explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPHEREx	all-sky near IR spectral survey
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SPT	South Pole Telescope
SPT3G	South Pole Telescope 3rd Generation
SPTpol	South Pole Telescope polarization instrument
SQUID	Superconducting Quantum Interference Devices
Super-CDMS	Super Cryogenic Dark Matter Search
Super-TIGER	Super Trans-Iron Galactic Element Recorder
TA	Telescope Array
TCAN	Theoretical and Computational Astrophysics Networks
TESS	Transiting Exoplanet Survey Satellite
TMT	Thirty Meter Telescope
TRL	technology readiness level
TSIP	Telescope Systems Instrumentation Program
URO	University Radio Observatories
UV	ultraviolet
VAO	Virtual Astronomical Observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLA	Very Large Array
VLBA	Very Long Baseline Array

VLT	Very Large Telescope
WFC3	Wide Field Camera 3
WFIRST	Wide Field Infrared Survey Telescope
WIMP	weakly interacting massive particle
WIYN	Wisconsin/Indiana/Yale/NOAO Telescope
WMAP	Wilkinson Microwave Anisotropy Probe
XMM	NASA's X-ray Multi-Mirror Mission
XMM-Newton	European Space Agency's X-ray Multi-Mirror Mission
XRP	Exoplanet Research Program (formerly OSS)

D

Biographies of Committee Members and Staff

COMMITTEE

JACQUELINE N. HEWITT, *Chair*, is a professor of physics at the Massachusetts Institute of Technology (MIT) and Director of MIT's Kavli Institute for Astrophysics and Space Research. She received her B.A. in economics from Bryn Mawr College and her Ph.D. in physics from MIT. After postdoctoral appointments at Haystack Observatory and Princeton University, she returned to MIT to join the faculty. Professor Hewitt's research interests are in the application of techniques of radio astronomy, interferometry, and signal processing to problems in astrophysics. She was one of the pioneers of wide-area radio surveys with the Very Large Array radio telescope, work that led to the discovery of the first Einstein ring gravitational lens. Her current research involves low-frequency radio studies of the "Cosmic Dawn," the formation of the first stars and galaxies, and surveys of transient astronomical radio emission. Dr. Hewitt received the 1993 Booker Prize from the International Union of Radio Science and the 1995 Maria Goeppert-Mayer Award from the American Physical Society (APS). She is a fellow of the American Academy of Arts and Science, a fellow of the APS, a former David and Lucile Packard Foundation fellow, and a former Alfred P. Sloan fellow. Dr. Hewitt chaired the 2010 Panel on Particle Astrophysics and Gravitation for the "New Worlds, New Horizons in Astronomy and Astrophysics" decadal survey, and she has served on the Space Studies Board (SSB) and the Board on Physics and Astronomy (BPA) of the National Academies of Sciences, Engineering, and Medicine.

ADAM S. BURROWS is a professor at Princeton University in the Department of Astronomical Sciences. He is also director of the Princeton Planets and Life Certificate Program, on the board of trustees of the Aspen Center for Physics, and is a fellow of the Princeton Center for Theoretical Science. His primary research interests are supernova theory, exoplanet and brown dwarf theory, planetary atmospheres, computational astrophysics, and nuclear astrophysics. Well known as a pioneer in the theory of exoplanets, brown dwarfs, and supernovae, Dr. Burrows has written numerous fundamental and influential papers and reviews on these subjects during the past 30 years. He has collaborated with more than 200 co-authors on more than 350 papers and given more than 300 invited talks and colloquia. He is a member of the National Academy of Sciences (NAS), a fellow of the American Academy of Arts and Sciences, a fellow of the American Association for the Advancement of Science (AAAS), a fellow of the APS, the 2010 Beatrice M. Tinsley Centennial Professor, and a former Alfred P. Sloan fellow. He has been a consultant for the American Museum of Natural History in New York and served as the chair of the Kavli Institute for Theoretical Physics Advisory Board, as co-chair of NASA's Universe Subcommittee, as chair of NASA's Origins Subcommittee, as co-chair of NASA's Strategic Roadmapping Committee "Search for Earth-like Planets," as co-chair of NASA's Origins/SEUS Roadmapping committee, and as a primary author of NASA 2003 Origins Roadmap. He received his B.S. in physics from Princeton University and his Ph.D. in physics from MIT. He has served as chair of the Academies' BPA as well as serving on the Committee on Astronomy and Astrophysics, Astro2010, the Rare Isotope Science Assessment Committee, and the Subcommittee on the Implementation of the DOE Long-Range Plan for Nuclear Physics.

NEIL J. CORNISH is a professor of physics at Montana State University in the Department of Physics. Previously, Dr. Cornish was a NASA research fellow at the Department of Astrophysical Sciences at Princeton University. Before moving to Princeton, he was a research fellow in Stephen Hawking's group at Cambridge University in England. His research focuses on the interface between general relativity, astrophysics, and early universe cosmology. Dr. Cornish's main area of research is the newly emerging field of gravitational wave astronomy. He is a member of the Laser Interferometer Gravitational Observatory (LIGO) scientific collaboration and the North American Nanohertz Gravitational Observatory (NANOGrav) collaboration. Dr. Cornish received his Ph.D. in physics from the University of Toronto. He served as a member on the Academies' Astro2010 Panel on Cosmology and Fundamental Physics.

ANDREW W. HOWARD is an assistant astronomer at the Institute for Astronomy at the University of Hawaii, Manoa. Dr. Howard is interested in the formation and evolution of planets orbiting stars other than the Sun and is particularly interested in the diversity of small planets. Prior to working at the University of Hawaii, he was a research astronomer and postdoctoral fellow with the University of California, Berkeley. He has received the University of Hawaii Regents' Medal for Excellence in Research and the Cozzarelli Prize. He received his B.S. in physics from MIT and an M.A and Ph.D. in physics from Harvard University.

BRUCE MACINTOSH is a professor of physics at Stanford University. His research focuses on the detection of extrasolar planets through direct imaging and on using adaptive optics to shape the wavefronts of light for a variety of applications. Dr. Macintosh is the principal investigator of the Gemini Planet Imager, an advanced adaptive optics planet-finder for the Gemini South Telescope. Prior to Stanford, he was a physicist at the Lawrence Livermore National Laboratory where he also completed his postdoctoral work. He received his Ph.D. in astronomy at University of California, Los Angeles. Dr. Macintosh served as a member on the Academies' Astro2010 Panel on Optical and Infrared Astronomy from the Ground and on the Committee on Astronomy and Astrophysics.

RICHARD F. MUSHOTZKY is a professor at the University of Maryland, College Park (UMD) in the Department of Astronomy. Prior to joining UMD, he was a senior scientist at NASA Goddard Space Flight Center (GSFC). His recent research has focused on understanding the triggering mechanisms in active galaxies, the nature of ultra-luminous X-ray sources and whether they are intermediate black holes, the evolution of active galaxies across cosmic time, the nature of the innermost regions around supermassive black holes, and the physics of clusters of galaxies and their use as tracers of metal production in the universe. Dr. Mushotzky is a member of the Astro-H science team, a new X-ray spectroscopic observatory being prepared for launch in early 2016, and has been involved in numerous high-energy astrophysics missions—most recently, Swift, Chandra, XMM, and Suzaku. He received his B.S. in physics from MIT and received his M.S. and a Ph.D. in physics from the University of California, San Diego. Dr. Mushotzky's previous service includes membership on the Academies' Astro2010 Panel on Galaxies Across Cosmic Time, the Committee on Astronomy and Astrophysics, the U.S. National Committee for the International Astronomical Union, the Task Group on Space Astronomy and Astrophysics, and the Panel on Cooperation with the USSR in High Energy Astrophysics.

ANGELA V. OLINTO is the Homer J. Livingston Professor of the Department of Astronomy and Astrophysics at the University of Chicago. She is also a member of the Enrico Fermi Institute and the Kavli Institute for Cosmological Physics at the University of Chicago. Dr. Olinto's interests are in theoretical astrophysics, particle and nuclear astrophysics, and cosmology. She is the U.S. principle investigator of the JEM-EUSO space mission and a member of the international collaboration of the Pierre Auger Observatory, both designed to discover the origin of the highest energy cosmic rays. She made significant contributions to the study of the structure of neutron stars, inflationary theory, cosmic magnetic fields, the nature of the dark matter, and the origin of the highest energy cosmic particles:

cosmic rays, gamma rays, and neutrinos. Dr. Olinto has served as chair of the Department of Astronomy and Astrophysics at the University of Chicago for two terms. She is a fellow of the APS and has served as chair of their Division of Astrophysics. She is a fellow of AAAS, has served as trustee of the Aspen Center for Physics, and is serving on the Astronomy and Astrophysics Advisory Committee. She received her Ph.D. in physics from MIT. Dr. Olinto served as a member on the Academies' Astro2010 Panel on Particle Astrophysics and Gravitation and the Committee on Scientific Assessment of Proposed U.S. Neutrino Experiments.

STEVEN M. RITZ is a professor of physics and the director of the Santa Cruz Institute for Particle Physics at the University of California, Santa Cruz (UCSC). He is a fellow of the APS and a recipient of the NASA Outstanding Leadership Medal, and he was a Sloan Foundation Fellow in Physics. Prior to joining the faculty at UCSC, he was an astrophysicist at NASA GSFC, where he served as the Fermi (nee GLAST) project scientist, and an adjunct professor at the University of Maryland. Before moving to NASA, he was an associate professor of physics at Columbia University. He chaired the Particle Physics Project Prioritization Panel (P5) for National Science Foundation and Department of Energy, and he is currently the Large Synoptic Survey Telescope camera project scientist. He received his B.A. in physics and music from Wesleyan University, his M.S. in physics from the University of Wisconsin, Madison, and his Ph.D. in physics from the University of Wisconsin, Madison. His prior Academies' membership includes the Panel on Implementing Recommendations from New Worlds New Horizons Decadal Survey and the Astro2010 survey committee.

ALEXEY VIKHLININ is deputy associate director at the Harvard-Smithsonian Center for Astrophysics of the High Energy Astrophysics Division. He is also an associate senior researcher at the High Energy Astrophysics division of Moscow's Space Research Institute. His main research area is X-ray studies of galaxy clusters and their applications for cosmology and physics of the intergalactic medium. His research also includes collaboration with the South Pole Telescope team on X-ray observations of clusters discovered by their Sunyaev-Zeldovich signal, improvements in the cluster mass calibration using weak lensing techniques, studies of interplay between stellar and gaseous baryonic components in clusters, helping theorists to improve the intracluster medium modeling in numerical simulations, and also helping to make sure that a next-generation all-sky X-ray survey (e.g., SRG/eRosita or WFXT) becomes a reality. In 1995, Dr. Vikhlinin came to the United States where his main research is on X-ray studies of galaxy clusters and their application for cosmology and the physics of the intergalactic medium. He was co-awarded the 2008 Rossi Prize from the American Astronomical Society for his work on cluster cosmology and cold fronts. He received his Ph.D. in astrophysics from the Moscow University. Dr. Vikhlinin is a member on the Academies' Committee on Astronomy and Astrophysics.

DAVID H. WEINBERG is Henry L. Cox Professor and Chair of Astronomy and Distinguished Professor of Mathematical and Physical Sciences at the Ohio State University in Columbus, Ohio. Dr. Weinberg is an observationally oriented theorist who works on large-scale structure, galaxy formation, the intergalactic medium, and observational probes of the matter and energy content and initial conditions of the universe. He joined Ohio State as an assistant professor in 1995 after postdoctoral positions at Cambridge, University of California, Berkeley, and the Institute for Advanced Study. He joined the Sloan Digital Sky Survey (SDSS) in 1992 and served as project spokesperson for SDSS-II and project scientist for SDSS-III. He is a fellow of AAAS and the APS. Other honors include the Ohio State University Distinguished Scholar Award and the American Astronomical Society's Lancelot Berkeley Prize. He was a member on the WFIRST Science Definition Team and plans to continue to contribute to the project in the future. He received a B.S. in physics from Yale University and a Ph.D. in astrophysical sciences from Princeton University. Dr. Weinberg served as vice chair of the Astro2010 Panel on Cosmology and Fundamental Physics.

RAINER WEISS is a professor emeritus at MIT. Previously, Dr. Weiss served as an assistant physics professor at Tufts University and has been an adjunct professor at Louisiana State University since 2001. Dr. Weiss is known for his pioneering measurements of the spectrum of the cosmic microwave background radiation, his inventions of the monolithic silicon bolometer and the laser interferometer gravitational wave detector, and his roles as a co-founder and an intellectual leader of both the Cosmic Background Explorer (COBE) Project and the LIGO (gravitational-wave detection) Project. He has received numerous scientific and group achievement awards from NASA, an MIT excellence in teaching award, the John Simon Guggenheim Memorial Foundation Fellowship, the National Space Club Science Award, the Medaille de l'ADION Observatoire de Nice, the Gruber Cosmology Prize, and the Einstein Prize of the APS. Dr. Weiss is a fellow of AAAS, the APS, and the American Academy of Arts and Sciences, and he is a member of the American Astronomical Society, the New York Academy of Sciences, and Sigma Xi. He received his B.S. and Ph.D. in physics from MIT. Dr. Weiss is a member of the NAS and has served on nine Academies' committees from 1986 to 2007, including the Committee on NASA Astrophysics Performance Assessment; the Panel on Particle, Nuclear, and Gravitational-wave Astrophysics; and the Task Group on Space Astronomy and Astrophysics.

ERIC M. WILCOTS is a professor and associate dean at the University of Wisconsin (UW), Madison, in the College of Letters and Sciences. He received his Ph.D. in astronomy and astrophysics from University of Washington before serving as a postdoctoral fellow at the National Radio Astronomy Observatory (NRAO). Dr. Wilcots served as chair of the Department of Astronomy at UW-Madison before becoming an associate dean in the College of Letters and Science. He is an observer with broad expertise in the gas content and evolution of galaxies and galaxy groups and the impact of massive stars on the evolution of galaxies. This work includes understanding the distribution and kinematics of neutral hydrogen in and around galaxies, the impact of massive stars on their environment, and the role of active galactic nuclei in the evolution of galaxy groups and structure. He brings knowledge about radio, optical, and infrared astronomy. Dr. Wilcots has served on the Users, Visitors, and Program Advisory Committees for NRAO. He was also a member of the Associated Universities, Inc. (AUI), the Committee on the Future of Radio Astronomy, and is now a trustee of the AUI board. He was a member of the science working group for the International Square Kilometer Array project and remains a member of the board of the Southern African Large Telescope. He has also served on the board of the Wisconsin-Indiana-Yale-National Optical Astronomical Observatory consortium. He was a member of the Academies' Committee on Astronomy and Astrophysics and a member on the Astro2010 Panel on Galaxies Across Cosmic Time.

EDWARD L. WRIGHT is the David Saxon Presidential Cahir in Physics and professor at the Department of Physics and Astronomy at the University of California, Los Angeles (UCLA). At UCLA, Dr. Wright has been the data team leader on COBE, a co-investigator on the Wilkinson Microwave Anisotropy Probe (WMAP), an interdisciplinary scientist on the Spitzer Space Telescope, and the principal investigator on the Wide-field Infrared Survey Explorer (WISE). Dr. Wright is well-known for his Cosmology Tutorial website for the informed public and his web-based cosmology calculator for professional astronomers. He earned his Ph.D. in astronomy from Harvard University. He is a member of the NASA and has served on the Academies' Beyond Einstein Program Assessment Committee, the Committee to study Autonomy Research in Civil Aviation, the Committee to study NASA's Planned Wide Field InfraRed Survey Telescope-Astrophysics Focused Telescope Assets program (WFIRST-AFTA), and the Committee for Review of the Federal Aviation Administration Research Plan on Certification of New Technologies into the National Airspace System. As well, Dr. Wright currently serves on the Committee on Achieving Science Goals with CubeSats.

A. THOMAS YOUNG is executive vice president, retired, at Lockheed Martin Corporation. He is also former chair of the board of SAIC. Mr. Young was previously the president and chief operating officer of Martin Marietta Corporation. Prior to joining the industry, Mr. Young worked for 21 years at NASA where he directed NASA GSFC, was deputy director of the Ames Research Center, and directed the

Planetary Program in the Office of Space Science at NASA Headquarters. Mr. Young received high acclaim for his technical leadership in organizing and directing national space and defense programs, especially the Viking program. He is currently a member of the National Academy of Engineering, an honorary fellow of the American Institute of Aeronautics and Astronautics, and a fellow of the American Astronautical Society. Mr. Young is a member of the NASA Advisory Council. He earned his B.S. in engineering from the University of Virginia and M.S. in management from MIT. Mr. Young's Academies' service includes current membership on the Committee on Astronomy and Astrophysics and the Committee on Achieving Science Goals with CubeSats. His prior Academies membership includes the Committee on Survey of Surveys: Lessons Learned from the Decadal Survey Process, the Committee on the Assessment of the Astrophysics Focused Telescope Assets (AFTA) Mission Concepts, the Planning Committee on Lessons Learned in Decadal Planning in Space: A Workshop, the Committee on the Planetary Science Decadal Survey: 2013-2022, the Panel on Implementing Recommendations from New Worlds, New Horizons Decadal Survey, the Committee on the Decadal Survey on Astronomy and Astrophysics 2010, and the SSB as vice chair.

STAFF

DAVID B. LANG*, Study Director,* is a senior program officer for the Academies' BPA and joined the Academies in 2004. Mr. Lang received a B.S. in astronomy and astrophysics from University of Michigan and a master's degree in engineering and public policy from University of Maryland. At the BPA, he has operated many large committees on scientific and technical policy issues including spectrum management and telecommunications, astronomy and astrophysics, plasma science, particle physics, plasma physics, and materials science. He also works with the board to identify pressing policy issues through discussions with policymakers and the science community.

KATIE DAUD is a research associate for the SSB and the Aeronautics and Space Engineering Board (ASEB). She comes to the SSB from the Smithsonian National Air and Space Museum's Center for Earth and Planetary Studies where she was a planetary scientist. A triple major at Bloomsburg University, Ms. Daud received a Bachelor of Science in planetary science and earth science, and a Bachelor of Arts in political science.

DIONNA WILLIAMS is a program coordinator with the SSB, having previously worked for the Academies' Division of Behavioral and Social Sciences and Education for 5 years. Ms. Williams has a long career in office administration, having worked as a supervisor in a number of capacities and fields. Ms. Williams attended the University of Colorado, Colorado Springs, and majored in psychology.

MICHAEL H. MOLONEY is the Director for Space and Aeronautics at the SSB and the ASEB of the Academies. Since joining the ASEB/SSB Dr. Moloney has overseen the production of more than 60 reports, including five decadal surveys, in astronomy and astrophysics, Earth science and applications from space, planetary science, microgravity sciences, and solar and space physics. He has also been involved in reviewing of NASA's space technology roadmaps and oversaw a major report on the rationale for and future direction of the U.S. human spaceflight program, as well as reports on issues such as NASA's strategic direction; lessons learned from the decadal survey processes; the science promise of CubeSats; the challenge of orbital debris; the future of NASA's astronaut corps; NASA's aeronautical flight research program; and national research agendas for autonomy and low-carbon propulsion in civil aviation. Since joining the Academies in 2001, Dr. Moloney has also served as a study director at the National Materials Advisory Board, the BPA, the Board on Manufacturing and Engineering Design, and the Center for Economic, Governance, and International Studies. Dr. Moloney has served as study director or senior staff for a series of reports on subject matters as varied as quantum physics, nanotechnology, cosmology, the operation of the nation's helium reserve, new anti-counterfeiting technologies for currency, corrosion science, and nuclear fusion. Before joining the SSB and ASEB in 2010, Dr. Moloney was associate director of the BPA and study director for the 2010 decadal survey for astronomy and astrophysics (*New Worlds, New Horizons in Astronomy and Astrophysics*). In addition to his professional experience at the Academies, Dr. Moloney has more than 7 years' experience as a foreign-service officer for the Irish government—including serving at Ireland's embassy in Washington and its mission to the United Nations in New York. A physicist, Dr. Moloney did his Ph.D. work at Trinity College Dublin in Ireland. He received his undergraduate degree in experimental physics at University College Dublin, where he was awarded the Nevin Medal for Physics. Dr. Moloney is a corresponding member of the International Academy of Astronautics and a Senior Member of the American Institute of Aeronautics and Astronautics. He is also a recipient of a distinguished service award from the National Academies of Sciences, Engineering and Medicine.

JAMES C. LANCASTER is the director of the BPA and acting director of the National Materials and Manufacturing Board. He joined the BPA as a program officer in 2008 and has been responsible staff officer for a number of studies, including the decadal survey on nuclear physics—*Nuclear Physics: Exploring the Heart of the Matter*, *An Assessment of the Science Proposed for the Deep Underground Science and Engineering Laboratory (DUSEL)*, *Research at the Intersection of the Physical and Life Sciences*, *Frontiers in Crystalline Matter: From Discovery to Technology*, and *Selling the Nation's Helium Reserve*. Prior to joining the BPA, Dr. Lancaster served on faculty at Rice University, where he taught introductory physics to science and engineering students, and as a staff researcher, where he participated in experimental investigations of the interactions of highly excited atoms with electromagnetic pulses and surfaces. In addition to his M.A. and Ph.D. degrees in physics from Rice University, Dr. Lancaster holds a B.A degree in economics from Rice University and a J.D. degree from the University of Texas School of Law. Prior to entering the field of physics, Dr. Lancaster practiced law for more than 12 years, specializing in the financial structuring and restructuring of businesses.