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COLLEGE OF SCIENCE
Astronomy
& Steward Observatory

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March 15, 2017

Dr. France A. Córdova, Director
National Science Foundation
4201 Wilson Blvd., Suite 1205
Arlington, VA 22230

Mr. Robert M. Lightfoot, Acting Administrator
Office of the Administrator
NASA Headquarters
Washington, DC 20546-0001

Mr. Richard Perry, Secretary of Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

The Honorable John Thune, Chairman
Committee on Commerce, Science and Transportation
United States Senate
Washington, DC 20510

The Honorable Lisa Murkowski, Chairwoman
Committee on Energy & Natural Resources
United States Senate
Washington, DC 20510

The Honorable Lamar Smith, Chairman
Committee on Science, Space and Technology
United States House of Representatives
Washington, DC 20515

Dear Dr. Córdova, Mr. Lightfoot, Secretary Perry, Chairman Thune, Chairwoman Murkowski, and Chairman Smith:

I am pleased to transmit to you the annual report of the Astronomy and Astrophysics Advisory Committee for 2016–2017.

The Astronomy and Astrophysics Advisory Committee was established under the National Science Foundation Authorization Act of 2002 Public Law 107-368 to:

(1) assess, and make recommendations regarding, the coordination of astronomy and astrophysics programs of the Foundation and the National Aeronautics and Space Administration, and the Department of Energy;

(2) assess, and make recommendations regarding, the status of the activities of the Foundation and the National Aeronautics and Space Administration, and the Department of Energy as they relate to the recommendations contained in the National Research Council's 2010 report entitled *New Worlds, New Horizons in Astronomy and Astrophysics*, and the recommendations contained in subsequent National Research Council reports of a similar nature;
(3) not later than March 15 of each year, transmit a report to the Director, the Administrator of the National Aeronautics and Space Administration, the Secretary of Energy, the Committee on Commerce, Science and Transportation of the United States Senate, the Committee on Energy and Natural Resources of the United States Senate, and the Committee on Science, Space, and Technology of the United States House of Representatives, on the Advisory Committee's findings and recommendations under paragraphs (1) and (2).

The attached document is the fourteenth such report. The executive summary is followed by the report, with findings and recommendations for NSF, NASA and DOE regarding their support of the nation's astronomy and astrophysics research enterprise, along with detailed recommendations concerning specific projects and programs.

I would be glad to provide you with a personal briefing if you so desire.

Sincerely yours, on behalf of the Committee,

Dr. Buell T. Jannuzi
Chair, Astronomy and Astrophysics Advisory Committee

cc: Senator Bill Nelson, Ranking Member, Committee on Commerce, Science and Transportation, United States Senate
Senator Maria Cantwell, Ranking Member, Committee on Energy & Natural Resources United States Senate
Representative Eddie Bernice Johnson, Ranking Member, Committee on Science, Space, and Technology, United States House of Representatives
Senator Richard Shelby, Chairman, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate
Senator Jeanne Shaheen, Ranking Member, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate
Representative John Culberson, Chairman, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives
Representative Jose Serrano, Acting Ranking Member, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives
Senator Lamar Alexander, Chairman, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate

Senator Dianne Feinstein, Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate
Representative Mike Simpson, Chairman, Subcommittee on Energy and Water Development and Related Agencies, Committee on Appropriations, United States House of Representatives
Representative Marcy Kaptur, Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, United States House of Representatives
Representative Brian Babin, Chairman, Subcommittee on Space, Committee on Science, Space, and Technology, United States House of Representatives
Representative Ami Bera, Ranking Member, Subcommittee on Space, Committee on Science, Space, and Technology, United States House of Representatives
Representative Barbara Comstock, Chairwoman, Subcommittee on Research and Technology, Committee on Science, Space and Technology, United States House of Representatives
Representative Daniel Lipinski, Ranking Member, Subcommittee on Research and Technology, Committee on Science, Space and Technology, United States House of Representatives
Senator Ted Cruz, Chairman, Subcommittee on Space, Science, and Competitiveness, Committee on Commerce, Science and Transportation, United States Senate
Senator Edward J. Markey, Ranking Member, Subcommittee on Space, Science, and Competitiveness, Committee on Commerce, Science and Transportation, United States Senate
Dr. James Ulvestad, Acting Assistant Director, Directorate for Mathematical and Physical Sciences, National Science Foundation
Dr. Thomas Zurbuchen, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration
Mr. Dennis Andrucyk, Deputy Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration
Dr. Paul Hertz, Director, Astrophysics Division, Science Mission Directorate, National Aeronautics and Space Administration
Dr. J. Stephen Binkley, Acting Deputy Director for Science Programs, Office of Science, U.S. Department of Energy
Dr. James Siegrist, Director, Office of High Energy Physics, Office of Science, U.S. Department of Energy
Dr. Glen Crawford, Division Director, Research and Technology Division, Office of High Energy Physics, Office of Science, U.S. Department of Energy
Dr. Kathleen Turner, Program Manager, Office of High Energy Physics, Office of Science, U.S. Department of Energy
Dr. Jo Handelsman, Associate Director for Science, Office of Science and Technology Policy, Executive Office of the President
Dr. Tamara Dickinson, Principal Asst. Director for Environment and Energy, Office of Science and Technology Policy, Executive Office of the President
Dr. Meredith Drosbeck, Asst. Director, Education and Physical Sciences, Office of Science and Technology Policy, Executive Office of the President
Dr. Kamela White, Program Examiner, NSF, Office of Management and Budget
Dr. Grace Hu, Program Examiner, NASA, Office of Management and Budget
Dr. Avital Bar-Shalom, Program Examiner, DOE, Office of Management and Budget
Dr. Ralph Gaume, Acting Division Director, Division of Astronomical Sciences, National Science Foundation

Dr. Edward Ajhar, Acting Deputy Division Director, Division of Astronomical Sciences, National Science Foundation
Dr. Christopher Davis, Program Director, Division of Astronomical Sciences, National Science Foundation

Astronomy and Astrophysics Advisory Committee Members:

Dr. Rachel Bean, Cornell University
Dr. Dieter Hartmann, Clemson University
Dr. David Hogg, New York University
Dr. Klaus Honscheid, The Ohio State University
Dr. Buell T. Jannuzi, University of Arizona, Steward Observatory (Chair)
Dr. Kelsey Johnson, University of Virginia
Dr. Lisa Kaltenegger, Cornell University
Dr. Brian Keating, University of California, San Diego
Dr. Shane Larson, Northwestern University
Dr. Rachel Mandelbaum, Carnegie Mellon University (Vice Chair)
Dr. William Smith, ScienceWorks International
Dr. Jean Turner, University of California, Los Angeles
Dr. Martin White, University of California, Berkeley

Report of the Astronomy and Astrophysics Advisory Committee

March 15, 2017

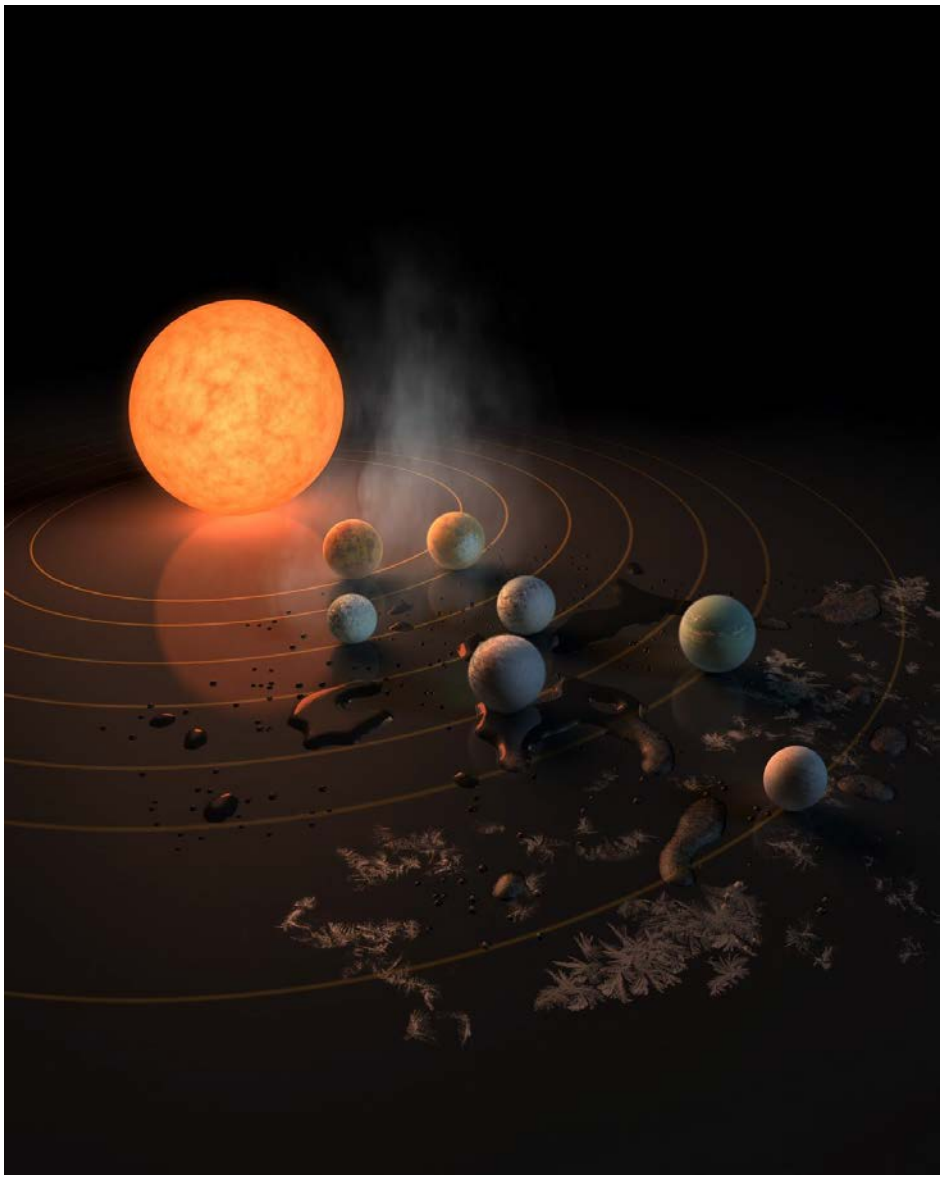

Image credit: NASA/JPL-Caltech

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Executive Summary

Astronomy and astrophysics research in our country has benefited tremendously from close coordination and collaboration between the US government and our talented community of researchers and educators based at colleges and Universities, non-federal observatories and research centers, and federally supported labs and centers. In addition to furthering our understanding of the Universe and enabling broad sharing of this knowledge, the concurrent investment in technological innovation and the well-educated workforce that are required to undertake our most ambitious research endeavors have yielded broad economic benefits to our country[1] and helped sustain US leadership in science.

The Astronomy and Astrophysics Advisory Committee (AAAC) commends the NSF, NASA, and DOE for their successful efforts, with the support of Congress and the American people, to provide balanced and coordinated investments in basic research and world leading facilities to further the priorities of the National Research Council (NRC) of the National Academies' decadal survey *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH)*. In recent years we have seen tremendous return on past investments, with results including the first direct detection of gravitational waves and the discovery of systems with planets in the habitable zones around distant stars. In this report we provide assessments of the progress made in the prior year toward future discoveries and make recommendations on how to sustain progress towards the goals and priorities of *NWNH*.

In particular, we recommend sustaining a balanced and coordinated investment by NSF, NASA, and DOE in the observational, theoretical, and computational research, technology development, and major projects and facilities, that are required to achieve the goals of *NWNH*. This includes the completion of construction, deployment, successful operation, and support of the researchers using the Daniel K. Inouye Solar Telescope (DKIST), the James Webb Space Telescope (JWST), the Large Synoptic Survey Telescope (LSST), and the Wide Field Infrared Survey Telescope (WFIRST). More broadly, providing (sometimes in partnership with others) the necessary support of US researchers and our most critical facilities, those identified in *NWNH* and associated reviews and reports, is essential to realizing the full scientific potential of the activities envisaged by *NWNH.*

We list our findings and recommendations below. The findings and recommendations are developed and supported in the body of the report. Acronyms are introduced in the text and are listed in Appendix A.

[1] William H. Press, "What's So Special about Science (and How Much Should We Spend on It?)", SCIENCE, Vol 342, 15 November 2013, page 817, http://science.sciencemag.org/; Peter Singer, "Federally Supported Innovations", ITIF, February 2014, https://itif.org/publications/2014/02/03/federally-supported-innovations

Collected Findings and Recommendations

Section 2

Finding: The continuing US investment in fundamental research by NSF, NASA, and DOE has enabled important new discoveries in astronomy and astrophysics, and extended the access to this science through public data releases and outstanding public interface efforts. Coordination between the agencies was particularly important in enabling these discoveries.

Section 3

Finding: US agencies are working well together to support the priorities of the astronomy and astrophysics research community, both in collaboration on large managed projects and through coordination of diverse research programs.

Finding: All current and planned cosmic surveys intend to publicly release their data and to provide suitable access tools which will further enhance the impact of these experiments.

Recommendation: We recommend that DOE, NSF, and NASA continue their successful cooperation in Astronomy and Astrophysics.

Finding: The tri-agency group considering LSST, WFIRST, and Euclid has begun the important process of coordinating between agencies by considering key parts of the dark energy science case for these missions and possible means of increasing the effectiveness of the missions in this area.

Recommendation: We recommend that the three agencies begin to develop a plan for including multiple stakeholders to consider the costs and benefits of coordination of LSST, WFIRST, and Euclid on the broad science areas these missions will advance.

Section 4

Finding: The inclusive community-based, National Academies-led, process of carrying out decadal surveys has tremendous value in ensuring that the resources provided by the federal government for research in astronomy and astrophysics are being effectively used to address the most important scientific priorities in the field and produce impactful results.

Finding: The AAAC endorses the findings and recommendations in *New Worlds, New Horizons: A Midterm Assessment (NWNH-AMA)*, and thanks the Mid-Decadal Panel for their work.

Finding: The AAAC applauds the agencies for their productive engagement with the community of researchers, through their inclusion in the review and advisory processes, that work with the agencies to further the field and maximize the return of the national investment in astronomy and astrophysics.

Section 4.1.1

Finding: The AAAC finds the movement of WFIRST toward Phase B start in October 2017 to be encouraging progress toward completing development of WFIRST in the mid-2020s.

Recommendation: The AAAC supports the recommendations of *NWNH* and *NWNH-AMA* that the NASA Astrophysics Division execute at least four Announcements of Opportunity for the Explorer program this decade, followed by Mission of Opportunity calls and mission selection, to preserve this valuable program of agile, low-cost missions in space.

Finding: The AAAC supports the outcome of NASA's Senior Review, is appreciative of the hard work by the Senior Review Panel, and commends NASA for its continuing engagement of the community in the oversight of its astrophysics operations.

Finding: The science priorities envisaged by *NWNH* as being addressed by LISA and IXO are beginning to be addressed by recent engagement by NASA in LISA and the ESA-led Athena X-ray observatory.

Section 4.1.2

Finding: The AAAC is gratified to see the substantial progress toward the highest priority decadal ground-based facility, LSST, which is advancing toward the start of survey science operations in 2022.

Finding: The AAAC applauds the efforts by NSF/AST to develop, sustain, and expand the Mid-Scale Innovations Program.

Recommendation: The AAAC continues to support NSF/AST's efforts to grow and develop the MSIP program, provided this is done while maintaining a balanced portfolio of investments by NSF/AST.

Section 4.1.3

Recommendation: The AAAC concurs with *NWNH-AMA* recommendation that the NSF facility divestment process be moved forward and that the agencies work to ensure that individual investigators are funded, in order to capitalize on and leverage the full capabilities of the large projects that represent such important and substantial investments by the agencies.

Recommendation: The AAAC supports the NSF approach of working to divest facilities to partners or non-federal organizations that will continue to operate them as scientific facilities.

Finding: The AAAC notes and supports efforts by NOAO, the LSST Project, AURA, NSF/AST, and the Kavli Foundation to implement the recommendations of the *OIR System Report*, including efforts such as the well-executed engagement of the community that resulted in the *Maximizing Science in the Era of LSST* report.

Section 4.2

Finding: The scientific justifications for the GSMT, ACTA, and CCAT continue to be strong and these projects are worthy of eventual support and participation by the federal government if funding opportunities become available to enable supporting one or more of these projects as part of a balanced program of investment by the agencies.

Recommendation: The AAAC supports efforts by AURA, NOAO, LSST, and NSF to implement the recommendations of the *OIR System Report*. We acknowledge that implementation of these recommendations will be constrained by the need to maintain a balanced investment across the portfolio of NSF/AST.

Finding: Increasing demand from scientific, commercial, and security interests for access to the same regions of the electromagnetic spectrum as those needed for astronomical research pose a challenge for managing spectrum access and ensuring astronomical research continues to be viable in necessary regions of the EMS.

Recommendation: The agencies should consider coordinating their separate efforts on advising on the use and protection of the electromagnetic spectrum to better protect access to the electromagnetic spectrum for astronomical and astrophysical research.

Section 4.3

Finding: The AAAC finds that the agencies have executed very efficiently the priorities of the decadal survey, given their budgetary constraints, with prioritization of projects that closely matches the intent of *NWNH*. The agencies make good use of supplemental reviews and standing advisory committees to inform their planning and decision-making.

Section 5

Finding: The CMB-S4 CDT, a subcommittee of the AAAC created at the request of DOE and NSF, is carrying out a valuable process of determining science and technical requirements to meet the CMB-S4 science goals and to develop a concept, including the technical and mission requirements, for a ground-based CMB-S4 experiment.

Finding: There is broad participation by members of the astronomy and astrophysics community, with agency support, in developing ideas for future experiments, missions, and programs to be undertaken in the coming decades, with the goal of producing well developed and well costed ideas and concepts to be considered by the 2020 decadal survey.

Recommendation: The AAAC supports the continued exploration, with the support of the agencies, into future directions and experiments, missions, and programs to be considered for support by the 2020 decadal survey.

Recommendation: The AAAC recommends that the agencies work with the National Academies to ensure a timely beginning to the next decadal survey, along with updates to the structure as recommended by *NWNH-AMA*.

Section 6

Finding: Major flight and construction programs may be harmed by continued uncertainty in the budget, leading to cost overruns and schedule slips. The AAAC urges that special attention be paid to these programs at the time that the FY 2017 budget is finalized and the FY 2018 budget is formulated.

Recommendation: In formulating their programs for FY 2018, NSF, NASA and DOE should strive to maintain viable research grant programs and preserve the highest priority decadal survey recommended programs.

Finding: The AAAC commends NSF/AST and NASA for devising and implementing plans aimed at reducing proposal pressure.

Recommendation: The committee recommends that NASA carefully monitor the impact of the planned changes to the prize fellowship and ATP solicitations (reduction in the number of prize fellowships offered annually and change in the frequency of ATP solicitations to every other year) to ensure that specific subfields within astronomy and astrophysics, such as theory, are not disproportionately affected.

Finding: At current budget levels the anticipated facilities operations costs are not consistent with a program balance that ensures scientific productivity. Conversely, even moderate increases in the NSF-AST grants budget would have a highly leveraged impact. The AAAC recognizes that this need will be even more difficult to fulfill if major budget reductions in FY 2017 and beyond materialize.

1. Introduction

The Astronomy and Astrophysics Advisory Committee (AAAC),[2] established in the National Science Foundation (NSF) Authorization Act of 2001, monitors and evaluates the performance of the NSF, National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE), on issues within the field of astronomy and astrophysics. The AAAC pays particular attention to those activities that require or would benefit from coordination of the agencies' efforts. The AAAC is further charged to provide an annual assessment of the progress of the agencies in implementing the recommendations of the most recent National Research Council (NRC) of the National Academies' decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*[3] *(NWNH),* its predecessors, and relevant reports from similarly constituted non-decadal advisory committees. Of particular relevance to the AAAC's charge this year is the midterm assessment[4] on progress towards achieving the goals of NWNH as conducted by the National Academies and discussed thoroughly in this report.

The AAAC reports its assessments and recommendations to the Secretary of Energy, the NASA Administrator, the NSF Director, and to relevant committees in the House and Senate. This communication represents the annual report of the 2016-2017 committee.

Some particularly notable research highlights from the past year are outlined in Section 2. The cover photo of this report illustrates one of those highlights, the recent announcement of the discovery of 7 Earth-sized worlds in the TRAPPIST-1 system, 39.5 light-years from Earth. The detected planets are tightly packed in orbits that are in apparent resonance, accounting for the stability of the system in such a small space. The system is remarkable for the fact that all the worlds are roughly Earth-sized, and three of them exist in the habitable zone of the parent star. The discovery and characterization of this remarkable system was enabled by a cross-agency and international coordination of observations at a variety of wavelengths, using data from the TRAPPIST telescope, Spitzer, Hubble, the Himalayan Chandra Telescope (HCT) in India, the Very Large Telescope (VLT) in Chile, and the UK Infrared Telescope (UKIRT) in Hawaii. Future observations could characterize the atmospheres of these worlds, using observations with JWST or instruments such as Wide-Field Camera 3 (WFC3) on Hubble. This kind of coordinated effort among science teams, institutions, agencies, and facilities illustrates the benefits of coordinated investments in scientific capability. Continued awareness and promotion of these tangible benefits as new facilities come online (e.g. LSST) will continue to maximize the scientific returns from investment in these facilities and programs.

Since March 15, 2016, the AAAC has had two face-to-face meetings and two video

[2] https://www.nsf.gov/mps/ast/aaac.jsp

[3] https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

[4] http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_161177

conferences. Representatives of the three agencies have given briefings and provided input on the status of their programs. We also received presentations from AURA regarding their plans for responding to a request from NSF to evolve how AURA manages their ground based OIR facilities for the NSF. As we finalize this report, the FY 2017 budget has not been passed and agencies are on a Continuing Resolution. DOE HEP Cosmic Frontier has a spending plan under the CR which has been presented; all the projects are expected to be executed on schedule. Currently, the FY 2017 NSF spending plan has not been presented or approved. The NASA Astrophysics Division is able to execute all of its planned programs, projects, and investigations under the continuing resolution. The FY 2018 President's budget request has not been released.

This 2017 annual report begins with a summary of selected accomplishments from the past year of agency-supported activities, some of which could not have been accomplished without interagency coordination. We further comment more generally on interagency coordination and cooperation, including on future astronomical surveys that will take place in the 2020s. This is followed by our assessment and recommendations regarding the progress upon the priorities and goals as outlined by the National Academies decadal surveys and reports, followed by an update on preparation for the next decadal survey. We conclude with a summary of the budget situation and its impact on future progress towards fulfillment of the vision in *NWNH*, including commenting on some attempts by NASA and NSF to reduce the proposal over-subscription rate.

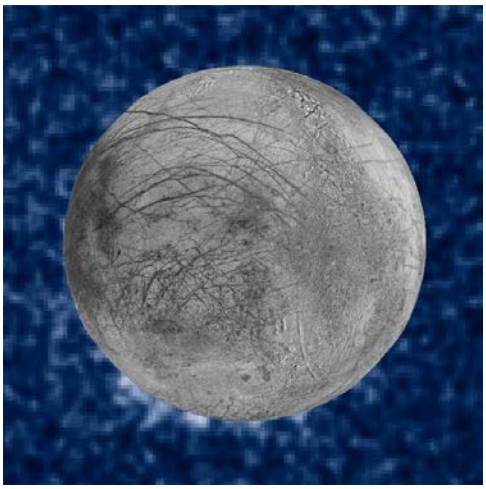
2. Science Highlights

Below is a non-exhaustive list of some of the most exciting breakthroughs in astronomy and astrophysics for the year covered by this report. These breakthroughs span a wide range of areas within the field, used resources at a range of wavelengths (e.g., radio and optical parts of the electromagnetic spectrum), and in many cases were only possible due to synergies between resources provided by at least two of the relevant agencies. Also included are highlights that resulted in the release of very large datasets for use of the entire astronomical community, and some exciting science outreach through citizen science.

Witnessing planetary formation:
Observations using the Atacama Large Millimeter Array (ALMA) of the very young star known as HD163296 have revealed gaps in both the gas and dust in the surrounding disk of material. These gaps indicate the presence of infant planets, with roughly the same mass as Saturn. Observations such as these are providing information on the processes that govern the formation of planets. (Isella et al. 2016, Phys. Rev. Lett. 117, 251101[5])

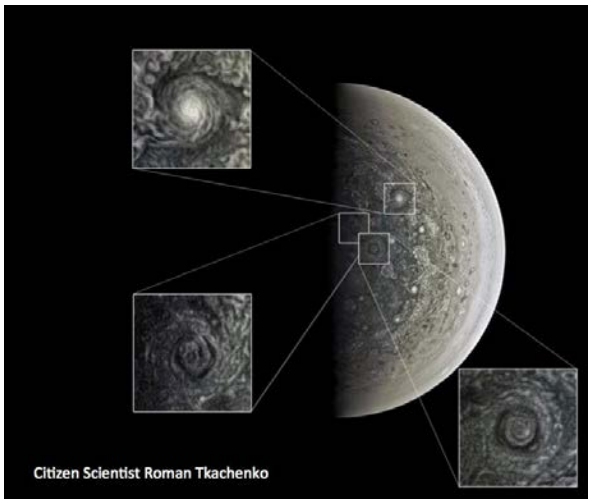
Discovery of the host galaxy of a mysterious Fast Radio Burst:
Fast Radio Bursts, discovered in 2007, are ultrafast and ultrabright bursts of radio emission. Only 18 such signals have been detected, and their origin has eluded astronomers. New observations that leveraged facilities supported by multiple agencies have identified the origin of the recent burst known as FRB121102 as a dwarf galaxy 2.5 billion light years away (Chatterjee et al. 2017, Nature 541, 58).[6]

[5] http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.117.251101
[6] http://www.nature.com/nature/journal/v541/n7635/abs/nature20797.html



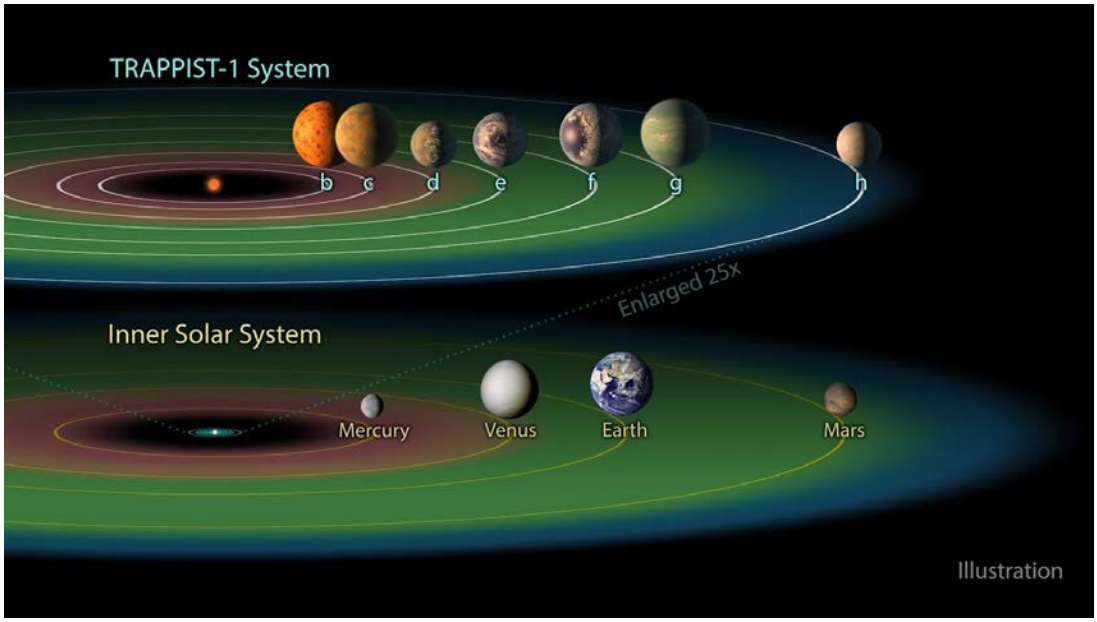
Water Plumes on Europa: Observations using the Hubble Space Telescope spotted 125-mile high water geysers erupting from Jupiter's moon, Europa. These results increase confidence in the existence of a water ocean under Europa's icy surface. Monitoring these intermittent geysers could provide guidance for the upcoming Europa mission in the 2020's. (Sparks et al. 2016, ApJ, 829, 121).[7]

Teachers Aboard! The SOFIA Airborne Astronomy Ambassador program works to enhance STEM education with a program including: a series of webinars, asynchronous content learning, and a series of hands-on workshops; an immersion experience at NASA Armstrong Flight Research Center's B703 science research aircraft facility; and ongoing participation in the AAA community of practice and connection to subject matter experts. Educators fly on SOFIA and participate in research with PI-led teams (http://www.seti.org/AAA).

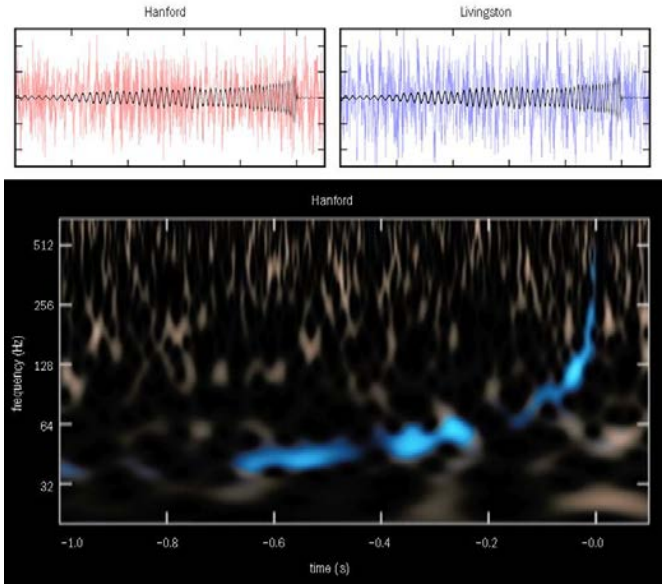


Citizen Science Enhancing Science: NASA's Juno mission is producing spectacular views of Jupiter's surface, and citizen scientists are helping to get the most out of the data. This image, produced by Roman Tkachenko, is helping to identify storms on Jupiter's South Pole. Programs like this give amateurs and enthusiasts an opportunity to contribute to the exploration of the universe.[8]

[7] http://iopscience.iop.org/article/10.3847/0004-637X/829/2/121/
[8] https://www.missionjuno.swri.edu/junocam

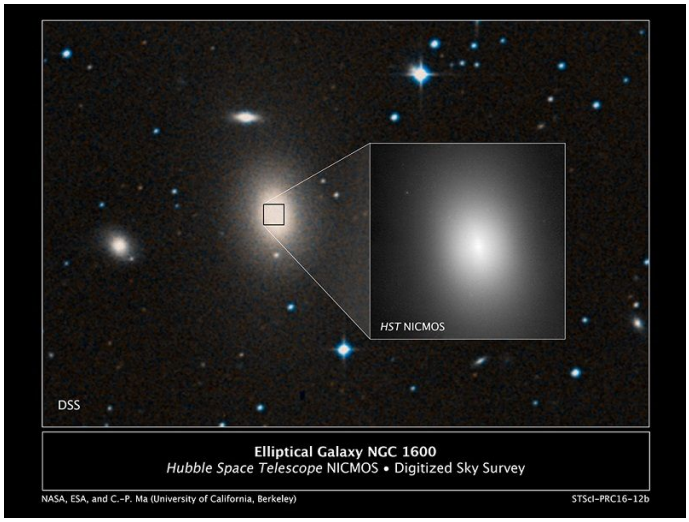


Seven Earth-Sized Planets in Single System:
NASA's Spitzer Space Telescope and a group of ground-based telescopes, some of which are supported by the NSF, have found a planetary system with seven rocky planets. Three of those are in the Habitable Zone and could be similar to Earth. These planets are orbiting a small star, known as an M-dwarf, only 40 light years from Earth. The discovery of this tightly packed rocky "solar system" will enable detailed follow-up studies by JWST, and ELTs to investigate their environments, and ultimately whether they may host life. (Gillon et al. 2017, Nature, 533, 221)[9] (Image credit: NASA/JPL-Caltech)

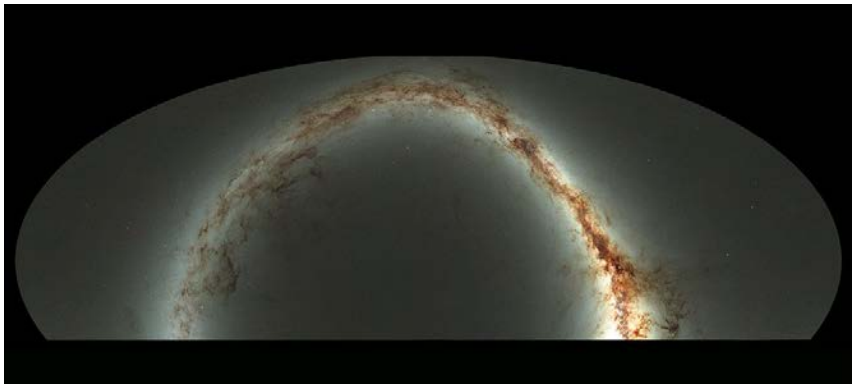


Advanced LIGO 2nd Detection: After its initial discovery, Advanced LIGO continued observing and made its second detection, the merger of 8 and 14 solar mass black holes, called GW151226 (the "Boxing Day" Event). These black holes are within the range of masses expected to form from normal stellar evolutionary processes (as opposed to the first detection, which had masses in the range of 30 solar masses). This detection shows the promise of gravitational wave observations as an observational tool for modern astronomy. (B.P. Abbott et al. (LIGO Scientific Collaboration & Virgo Collaboration), 2016, PRL 116, 241103).[10]

[9] http://www.nature.com/nature/journal/v533/n7602/full/nature17448.html
[10] http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.241103

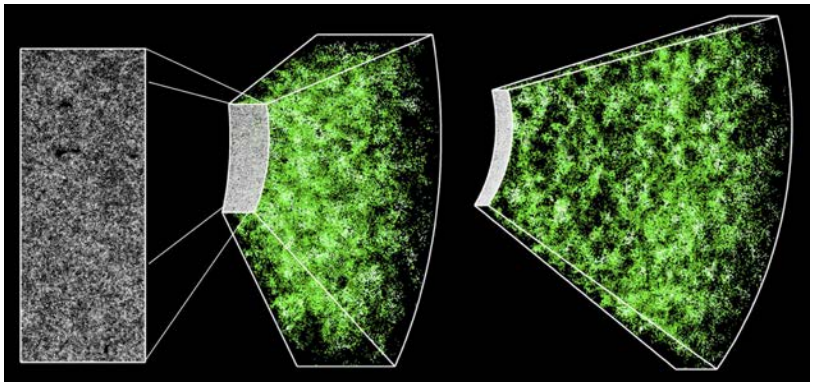


Supermassive Black Hole in NGC 1600: Using spectra from multiple observatories (including NSF's Gemini North and the McDonald Observatory), and surface photometry from NSF's KPNO and the Hubble Space Telescope, an international team of observers measured a 17 billion solar mass black hole in the center of galaxy NGC 1600. The unusual nature of this discovery is that NGC 1600 is an isolated, small elliptical galaxy. The SMBH accounts for roughly 2 percent of the total galaxy mass, and is about 10 times larger than expected when compared to the host galaxies of black holes of similar mass (Thomas et al. 2016, Nature 532, 340).[11]

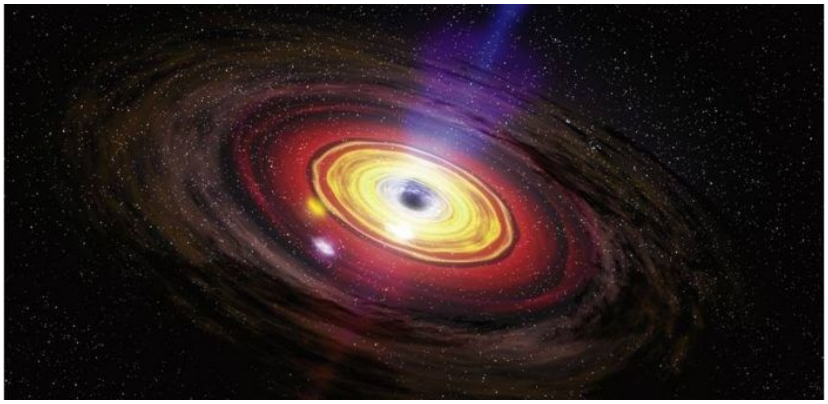


Pan-STARRS Digital Sky Survey Release: Pan-STARRS released the data from the Pan-STARRS 1 Surveys[12], constituting the largest digital sky survey ever released. Consisting of millions of images and their associated catalogs, with billions of precision measurements of stars and galaxies. The data span four years and is about two petabytes in size (roughly 100 times the information content contained in Wikipedia). The survey data are hosted by the Mikulski Archive for Space Telescopes (MAST), NASA's primary repository for optical and UV observations, based on an agreement between NSF (which funded the completion of the survey) and NASA. This is an excellent example of the two agencies working together to efficiently maximize the scientific impact of a significant federally enabled science project.

[11] http://www.nature.com/nature/journal/v532/n7599/full/nature17197.html
[12] Press release: http://www.ifa.hawaii.edu/info/press-releases/panstarrs_release/
Data: http://panstarrs.stsci.edu



Sloan Digital Sky Survey-III Baryon Oscillation Spectroscopic Survey (SDSS-III BOSS) results: In mid-2016, the BOSS survey released constraints on the accelerated expansion of the Universe based on a map containing 1.2 million galaxies with precise redshift measurements. These are the most precise results to date using this particular method of measuring the expansion rate of the Universe. Image credit: Jeremy Tinker and the SDSS-III collaboration[13].



Blazars in the early Universe: Significant progress on the DOE and NASA supported Fermi Gamma-ray Space Telescope mission has resulted from their implementation of the Pass 8 data analysis package for event reconstruction. Pass 8 increases sensitivity and, more importantly, increases the energy range of this gamma-ray mission. As all data are stored, reprocessing of the existing data with the refined Pass 8 software transformed Fermi into a "new" mission. The improved capability has been used with especially high impact in studies of extragalactic sources, blazars in particular. Several new blazars were detected in the early Universe (M. Ackermann et al. 2017, ApJL 837, L5) as a result of the new analysis software. Image credit: NASA/Dana Berry (SkyWorks Digital).

Finding: The continuing US investment in fundamental research by NSF, NASA, and DOE has enabled important new discoveries in astronomy and astrophysics, and extended the access to this science through public data releases and outstanding public interface efforts. Coordination between the agencies was particularly important in enabling these discoveries.

[13] http://www.sdss.org/press-releases/astronomers-map-a-record-breaking-1-2-million-galaxies-to-study-the-properties-of-dark-energy/

3. Overview of Interagency Coordination and Cooperation

For many decades astronomy and astrophysics have been areas of strong interagency coordination and cooperation. The era of cosmic surveys that started in 1990 with the Sloan Digital Sky Survey (SDSS) is an excellent example of the three agencies working cooperatively. An ongoing large sky survey, the Dark Energy Survey (DES), is currently collecting data and has produced scientific results, while the Dark Energy Spectroscopic Instrument (DESI) and the Large Synoptic Survey Telescope (LSST) are now under construction. All of these surveys received support from more than one agency and many (DES, DESI, and LSST) are the result of coordinated collaborative support and effort involving multiple agencies and groups of scientists. These major survey projects, which have transformed (SDSS) or have the potential to transform not only astronomy and astrophysics, but also related fields in science and computation (e.g. LSST), would not have been feasible without the coordinated collaborative efforts of more than one agency. In the case of DES, DESI, and LSST, the relevant coordination was between the NSF and DOE. NASA also partners with both of the other agencies. For example, the Fermi Gamma-ray Space Telescope had its principal instrument built in partnership with DOE and has support from DOE for Fermi-GLAST operations, and its science mission was enhanced and supported by ground-based follow-up and supporting observations from NSF and NASA supported facilities. NASA's very high resolution NEID spectrograph for the WIYN 3.5 m telescope on Kitt Peak, operated by a partnership between the University of Wisconsin, Indiana University, University of Missouri, NASA, and NSF/AURA/NOAO; will amplify the science impact of the TESS spacecraft. The Hubble Space Telescope routinely makes observations that benefit from complementary observations from the ground, including many NSF and NASA supported facilities.

Finding: US agencies are working well together to support the priorities of the astronomy and astrophysics research community, both in collaboration on large managed projects and through coordination of diverse research programs.

Much of the success of digital sky surveys, starting with the Sloan Digital Sky Survey, has come from unanticipated impacts enabled by broad access and thoughtfully conceived databases and tools. Benefits and scientific gains outweigh the cost to the projects to provide the required tools. All current surveys, including those under construction, plan to publicly release their data. The data availability is consistent with the AAAC Principles for Access[14], recommended by the AAAC in their 2013-2014 annual report.

Finding: All current and planned cosmic surveys intend to publicly release their data and to provide suitable access tools which will further enhance the impact of these experiments.

[14] https://www.nsf.gov/mps/ast/aaac/aaac_2014_principles_for_access-v2.pdf

New opportunities for interagency operations will arise when the next generation of survey instruments and telescopes comes online. High quality data from NASA's WFIRST satellite, the European Euclid mission, and LSST (NSF, DOE) may lead to even larger gains if observations are combined early at the raw data level and processed jointly. This has led to an inter-project/inter-agency task force discussed in section 3.B of this report.

Future experiments studying the cosmic microwave background (CMB) may benefit from interagency cooperation and coordination (see also section 5.1 of this report).

In conclusion, the state of interagency cooperation and coordination is strong.

Recommendation: We recommend that DOE, NSF, and NASA continue their successful cooperation in Astronomy and Astrophysics.

As one example that will benefit from continued coordination, the LSST, Euclid and WFIRST projects have very strong overlap in the science that they plan to do, although the designs exhibit complementarity. In order to coordinate activities amongst the agencies, a "Tri-Agency Group" (TAG; an agency-only group) and "Tri-Project Group" (used to refer to the inclusion of project leaders) have been holding informal telecons every two months with yearly face-to-face meetings. To date the focus has been primarily on the dark energy science. It could be beneficial to a broader range of high priority science areas (as represented in the decadal surveys) if other stakeholders were brought into the process.

In addition to the TAG, the Euclid and LSST projects have been continuing attempts at coordination at the project level. Coordination is delicate due to the requirements of international agreements and the constraints on data rights within the projects. Coordination between these projects is still in its early stages.

Coordinating the cadence and survey footprints could lead to an increase in the science output. This needs to be further studied to quantify the gains that could be achieved for the many science areas, along with any risks should one of the projects not deliver to the assumed level. Informal discussions within and between the projects have begun on whether out-of-scope, low level joint data processing could be beneficial to some of the science areas. There could be many synergies between the projects in theoretical and data analysis investigations, though this has only just begun to be explored.

The AAAC welcomed the update on the progress being made in coordination, and looks forward to hearing about future progress, ideally involving coordination not only in the cosmology arena, but with respect to other astrophysics goals that these missions share.

Finding: The tri-agency group considering LSST, WFIRST, and Euclid has begun the important process of coordinating between agencies by considering key parts of the dark energy science case for these missions and possible means of increasing the effectiveness of the missions in this area.

Recommendation: We recommend that the three agencies begin to develop a plan for including multiple stakeholders to consider the costs and benefits of coordination of LSST, WFIRST, and Euclid on the broad science areas these missions will advance.

4. Implementation of Decadal Survey Recommendations

The reports of the National Academies decadal surveys in Astronomy and Astrophysics present the community's consensus view of the scientific opportunities in the coming decade and a list of goals to be achieved. In addition, the reports provide a prioritized road map for the missions, major facilities, research capabilities, and experiments necessary to realize the scientific aspirations captured in the reports. The attention and respect given these reports are a reflection of the broad community involvement, effort, and care that went into their preparation.

The tremendous advancement in our field over the past sixty years is in large part due to the willingness of the federal agencies that have supported astronomy and astrophysics to work with the community to implement, within funding constraints, the plans outlined in these reports. This coordinated leveraging of investments for the commonly identified priorities has been very powerful in enabling so many of the aspirations of our community to become a reality, while bringing ancillary benefits in innovative technology development, economic return, and education in STEM and related fields.

Finding: The inclusive community-based, National Academies-led, process of carrying out decadal surveys has tremendous value in ensuring that the resources provided by the federal government for research in astronomy and astrophysics are being effectively used to address the most important scientific priorities in the field and produce impactful results.

The most recent survey report, 2010, is titled *New Worlds, New Horizons in Astronomy and Astrophysics* (*NWNH*). Like its predecessors, this report provided guidance for the NASA Astrophysics Division (NASA/APD), the NSF Astronomy (NSF/AST) division of the Directorate for Mathematical and Physical Sciences (NSF/MPS) and selected aspects of the physics programs at the NSF and DOE that have strong overlap with astronomy and astrophysics. These include the Office of High Energy Physics (HEP) of the DOE, which looks to the decadal survey reports for scientific priorities and new projects. The report also provides members of Congress and the American public an opportunity to review our assessment and advice regarding the implementation of the decadal surveys' recommendations.

The *NWNH* report recommended a plan for 2012-2021 that is organized around three key science themes: "searching for the first stars, galaxies, and black holes; seeking nearby habitable planets; and advancing understanding of the fundamental physics of the universe."[15] Presented in the report is a comprehensive plan that seeks to lay the groundwork for the decade ahead at the time of their report. Their program included activities in space and on the

[15] See page 2 of *NWNH*.

ground, classified according to scale. There were eleven unranked recommendations for small-scale activities, including several that targeted the development of technology and instrumentation for the future. There were three medium-scale and eight large-scale activities, tied closely to the three science themes. Of the eight large-scale activities, four are space-based and four are ground-based. Two of the space-based and two of the ground-based activities are being implemented (in one case at reduced scope), as described in section 4.1, while two of each have not yet been implemented, as described in section 4.2.

These National Academies decadal surveys proposed plans for implementation are understandably constrained by our community's ability, in collaboration with the federal government, to predict future levels of support and the scientific progression of our field. For these and other reasons, the community has worked with the federal agencies and Congress to provide timely evaluations and advice regarding the implementation of the recommendations of the decadal surveys during each decade. The AAAC is one of the groups, charged by Congress, to assist in this process, providing an annual assessment[16] of the progress toward realizing the decadal survey aspirations.

However, the AAAC is not the only group charged to provide assessments and recommendations to the government between reports of the decadal surveys. Each agency has review or advisory committees, standing or ad hoc, that provide oversight or advice, often communicated through reports that are valuable to us in meeting our charge to be aware of the activities of all three agencies. In addition, there is another FACA committee, the High Energy Physics Advisory Panel (HEPAP), that provides guidance and recommendations on the US High Energy Physics and Particle Physics programs - to DOE/HEP and NSF/PHY. In fact, HEPAP provides the primary advice to guide the DOE-HEP program. Through their advice to the agencies, all of these other panels and committees influence the priorities from the decadal survey that are being addressed during the current decade. Finally, the National Academies carried out two studies on Euclid[17] and WFIRST[18] in the context of *NWNH*. The reports that we referenced and used to inform our understanding of the evolution of the collective effort to realize the vision presented in *NWNH* include the following:

-- *Advancing Astronomy in the Coming Decade: Opportunities and Challenges.* Shortly after the release of *NWNH,* the National Science Foundation Division of Astronomical Sciences formed the Portfolio Review Committee (PRC), as recommended in *NWNH*. A catalyst for forming the committee was the realization that the models of the funding to be provided to NSF in the coming decade that had been assumed by the decadal survey were unlikely to be realized. The NSF sought expert advice from the community regarding how to try and maintain a balanced

[16] https://www.nsf.gov/mps/ast/aaac/archived_aaac_annualreports.jsp
[17] https://www.nap.edu/catalog/13357/assessment-of-a-plan-for-us-participation-in-euclid
[18] https://www.nap.edu/catalog/18712/evaluation-of-the-implementation-of-wfirstafta-in-the-context-of-new-worlds-new-horizons-in-astronomy-and-astrophysics

distribution of support to small, medium, and large programs while also sustaining a viable number of grants to individual investigators. The challenge of supporting the operations costs of existing facilities while taking on additional costs for new major facilities being commissioned is a challenge for NSF/AST at current funding levels. The PRC provided expert advice from the community regarding how NSF/AST should proceed when faced with some difficult choices. The PRC report was presented August 14, 2012 and is also known as the *Portfolio Review Committee Report*[19]. The PRC provided recommendations and further prioritized where efforts should be made to reduce costs to NSF/AST, while attempting to continue to retain valuable astronomical research capabilities in the system of facilities conducting astrophysical research.

-- *Optimizing the US Ground-Based Optical and Infrared Astronomy System: NWNH* included a recommendation that "NSF should request a report led by the Committee on Astronomy and Astrophysics (CAA) to help define a revised national ground based OIR system with a focus on the required instruments, telescopes, and public access to enable both the best science and broadest community participation in the LSST era. The NRC, in response to a request from NSF/AST, convened the "Committee on a Strategy to Optimize the US Optical and Infrared System in the Era of the Large Synoptic Survey Telescope (LSST)," to meet this recommendation. Their 2015 report, *Optimizing the US Ground-Based Optical and Infrared Astronomy System* (also known as the *OIR System Report*[20] or *Elmegreen Report)* included seven prioritized recommendations. One of their recommendations was that additional focused community involved planning and consultation activities should be undertaken, led by NOAO, to further refine the observing capabilities (instrumentation, telescope, software, event brokers, etc.) that would be needed to maximize the scientific impact and legacy of LSST. Such efforts have begun, starting with the NOAO and LSST Project Office organized Kavli Futures Symposium, "Maximizing Science in the Era of LSST: A Community-Based Study of Needed US OIR Capabilities." Their recommendations are available in their 2016 report, *Maximizing Science in the ERA of LSST*[21].

-- *Building for Discovery: Strategic Plan for US Particle Physics in the Global Context:* DOE HEP receives programmatic advice from two FACA committees, the AAAC and the High Energy Physics Advisory Panel (HEPAP). The DOE HEP divides its scientific program into three broad areas of scientific inquiry, or "Frontiers," as well as a Theory subprogram, Accelerator research and Detector R&D. Cosmic Frontier programs are primarily focused on two specific areas within astrophysics: understanding the nature of dark matter and the cosmic acceleration. The Particle Physics Project Prioritization Panel (P5) is a subpanel of HEPAP, that generates decadal strategic plans for high energy physics. The most recent report from P5 was released in 2014[22]. The entirety of the DOE HEP program is under the guidance of the strategic plan from HEPAP/P5, though in the case of the Cosmic Frontier, *NWNH* is used to identify opportunities

[19] https://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf

[20] https://www.nap.edu/catalog/21722/optimizing-the-us-ground-based-optical-and-infrared-astronomy-system

[21] https://www.noao.edu/meetings/lsst-oir-study/files/Maximizing_Science_in_LSST_era.pdf

[22] https://science.energy.gov/hep/hepap/reports/

for partnerships with NASA and NSF on projects that address the scientific goals of multiple agencies. *NWNH* was the first decadal survey in which DOE participated, due to the increasing impact of DOE research upon and involvement in cosmology. The HEPAP and its subpanels (e.g., P5) are still the primary mechanism that the DOE uses for receiving and responding to community input.

-- *NASA Senior Reviews:* The NASA 2016 Senior Review,[23] is the most recent example of NASA's regular review of active missions. Every two years the NASA Science Mission Directorate (SMD) undertakes an independent assessment of its current portfolio of active missions with the goal of determining how to maximize the scientific return from these missions within the available finite resources. The findings and recommendations of the Senior Reviews are used to set the implementation strategy and program plan for the missions for the following four years.

-- *New Worlds, New Horizons: A Midterm Assessment* (*NWNH-AMA*). *NWNH* anticipated that during the decade following their report scientific discoveries would be made, agency budgets would evolve, and technology developments and the rate of progress of missions and facility development would be variable enough to justify a need for assessment of progress and the viability of the goals and recommendations set forth in *NWNH.* For these reasons, *NWNH* included a recommendation for a mid-decadal detailed assessment of the progress toward realizing the aspirations of *NWNH.* The National Academies conducted a mid-decadal review of progress towards the goals set out in *NWNH*, as commissioned by NASA, NSF, and DOE. The fundamental finding of the delivered Mid-Decadal Report, *New Worlds, New Horizons: A Midterm Assessment* (*NWNH-AMA*) are that progress toward the goals set forth has been limited. This is from a combination of factors that involve the *NWNH* budget assumptions for NSF, which were too optimistic, and delays for JWST in the case of NASA.

Finding: The AAAC endorses the findings and recommendations in *New Worlds, New Horizons: A Midterm Assessment (NWNH-AMA)*, and thanks the Mid-Decadal Panel for their work.

The *Portfolio Review* and *OIR System Report* were advisory to NSF/AST. The *P5* is advisory to DOE and NSF. The Senior Reviews are advisory to NASA. *NWNH-AMA,* like *NWNH* and the reports of the *AAAC,* is intended to provide advice for all three of the agencies and as a result, we view it as a particularly important guide.

Finding: The AAAC applauds the agencies for their productive engagement with the community of researchers, through their inclusion in the review and advisory processes, that work with the agencies to further the field and maximize the return of the national investment in astronomy and astrophysics.

[23] https://science.nasa.gov/astrophysics/2016-senior-review-operating-missions/

We have extracted and considered from the above reports the active and still pending recommendations for the coming decade. In the following subsections we evaluate and comment upon the progress made during the past year on implementing the priorities of the community as represented in these reports, both for facilities and programs, as well as identify those projects or areas where efforts still need to be initiated.

In the following sections, we present the assessment of the AAAC of the efforts of the three agencies to implement the recommendations of *NWNH* as modified by the *Portfolio Review*, the *OIR System Report*, and the *NWNH Midterm Assessment.* We also include status reports and assessments regarding facilities or programs that were priorities of previous decadal surveys. We separate the discussion into two groups, an evaluation of those priorities that the agencies have started or completed addressing (section 4.1) and those that, for a variety of reasons, remain unaddressed (section 4.2). Finally, we summarize the committee's view of progress on the goals set forth in *NWNH* in section 4.3.

4.1 Priorities Addressed or Under Implementation

Below we summarize the state of progress for the highest priority large projects and initiatives identified by *NWNH* or its predecessor reports, as informed by other reports as noted above, for which the agencies have made some progress on implementation. We subdivide our discussion of the status of completed or in progress efforts into projects characterizable as "Space-based", "Ground-based", and "Other Initiatives or Programs".

4.1.1 Space-based Projects

The programs and initiatives discussed in this section are roughly ordered, but not perfectly, in reverse anticipated order of completion or launch. Ongoing programs or missions that were highlights of past decadal surveys are included when the AAAC believed they are either still scientifically particularly relevant to the developing new initiatives (that is they provide context) or impact the availability of funding for new initiatives. The programs or missions discussed in this section are all in progress or active. Programs that are recommended, but upon which work has not begun are discussed in section 4.2.

The *Wide-Field Infrared Survey Telescope* (*WFIRST*): *WFIRST* will be a space telescope with a large field of view designed to address all three *NWNH* themes in dark energy, exoplanets and galaxy evolution science. As the most highly ranked space-based project in *NWNH*, *WFIRST* is moving forward. The project is progressing more slowly than anticipated because the budget was not available in the first half of the decade due to the growth in cost

and schedule of JWST (see below). After this delayed beginning, which was used profitably to develop the next generation of detectors and mature coronagraph technology, the mission scope and design changed markedly compared to what was in *NWNH*.

Finding: The AAAC finds the movement of *WFIRST* toward Phase B start in October 2017 to be encouraging progress toward completing development of *WFIRST* in the mid-2020s.

***James Webb Space Telescope (JWST)*:** The *JWST* was the top space-based recommendation of the previous decadal survey, *Astronomy and Astrophysics in the New Millennium* (2001), and NASA subsequently committed to the project. The complexity and enormity of the effort meant that this responsibility continued into the *NWNH* decade, engendering constraints on NASA not fully accounted for at the time of the *NWNH* survey and its generation of a prioritized set of recommendations. *JWST* will be the most powerful telescope ever launched into space. Its four science instruments will operate in the near- and mid-infrared, where light is able to penetrate regions of gas and dust and study of highly redshifted stars and galaxies of the early Universe. In 2016 the science telescope and instruments were completed and spacecraft assembly was nearly completed. Cryo-vacuum testing will take place at Johnson Space Center in 2017, and the call for Early Release Science and Cycle 1 proposals will take place. *JWST* is on track for its planned October 2018 launch date.

Explorers Program Augmentation: This NASA program of relatively low-cost missions, quickly deployed, has a history of high scientific impact, including the Nobel Prize in 2006 for the Principal Investigators of the Cosmic Background Explorer. A high priority of *NWNH* was a significant expansion of the existing NASA Explorer program, including at least four Explorer Announcements of Opportunity during this decade, each with Mission of Opportunity calls and mission selection. The first Announcement of Opportunity was canceled before selection due to reductions in the NASA astrophysics budget. A second has allowed a Small Explorer mission (Imaging X-ray Polarimetry Explorer) to be approved into Phase B for launch in 2020, and Mission of Opportunity Phase A studies to be conducted for two projects. A third was released in 2016, and proposals for Medium-class Explorer missions and Missions of Opportunity are currently under review by NASA. A fourth is planned for 2018 or 2019. *NWNH-AMA* reiterated that NASA should preserve this goal to provide opportunities for the rapid realization of new scientific opportunities in space.

Recommendation: The AAAC supports the recommendations of *NWNH* and *NWNH-AMA* that the NASA Astrophysics Division execute at least four Announcements of Opportunity for the Explorer program this decade, followed by Mission of Opportunity calls and mission selection, to preserve this valuable program of agile, low-cost missions in space.

Euclid: Euclid is a European Space Agency-led mission with a focus on cosmic acceleration and dark energy scheduled to launch in 2020, with important instrumentation contributions from NASA. Three US science teams were selected by NASA to participate in the Euclid mission in 2013; the 54 people on these teams were given membership in the 1300 member Euclid Consortium (this includes 10 people at DOE labs). US participation in the EC now stands at about 80 people. In addition to the NASA-funded science participation, NASA is in the process of delivering 20 H2RG-based sensor chip systems (detector, associated electronics, and cryogenic cable) for the Euclid near infrared instrument and is funding a US-based node of the distributed data processing architecture. The US participation in the Euclid mission was not prioritized in *NWNH* because the mission had not yet been selected to move forward by ESA. However, a study by the National Academies, *Assessment of a Plan for U.S. Participation in Euclid* (NRC, 2012),[24] recommended that NASA should make a hardware contribution to the Euclid mission to enable US participation in the context of a strong US commitment to move forward with WFIRST, in order to fully realize the science priorities of *NWNH*.

NASA's SOFIA: While not strictly a space based mission, the Stratospheric Observatory for Infrared Astronomy (SOFIA) is a 2.5 meter telescope on a Boeing 747 that is operated by NASA. SOFIA operates at mid and far-infrared wavelengths that are otherwise only accessible from space, a spectral region covering the peak wavelengths at which interstellar dust emits and the most important spectral lines for cooling of the interstellar medium. Jointly funded by NASA and the German Aerospace Center, SOFIA is in 5 year prime operations. The US-provided High-resolution Airborne Wideband Camera-plus (HAWC+) instrument, as well as the upgraded Germany-provided GREAT Terahertz (upGREAT) array, were commissioned in 2016. Development of the next generation US-provided instrument, the High Resolution Mid-Infrared Spectrometer (HIRMES), was initiated in 2016. The next SOFIA instrument solicitation is planned for mid-2017.

Other Operating Missions: In 2016 February and March, NASA performed a Senior Review of most of its operating astrophysics space missions. Some of these missions are partnerships, including notable successes like *Fermi,* which includes contributions from DOE and international partners (Japan, Germany, France, Italy, and Sweden). Most of these missions were at some point in the past a recommendation of one or more decadal survey or competitively selected through an Explorers Program announcement of opportunity. The Senior Review involved a great deal of effort, with the ongoing missions delivering substantial self-analyses and proposals, and the Senior Review Panel deliberating the continuation, extension, or close-out of each. The recommendations of the Senior Review were to continue the existing missions (*HST, Chandra, Fermi, NuSTAR, Swift, and XMM-Newton)*, but two, *K2* and *Spitzer*, were recommended for continued operation until FY 2019, at which point they should conduct an orderly close-out with specific, well-justified end dates.

[24] https://www.nap.edu/catalog/13357/assessment-of-a-plan-for-us-participation-in-euclid

Finding: The AAAC supports the outcome of NASA's Senior Review, is appreciative of the hard work by the Senior Review Panel, and commends NASA for its continuing engagement of the community in the oversight of its astrophysics operations.

Finally, we discuss two *NWNH* recommendations that could not be pursued with precisely the originally-suggested timing or form, but that have recently been started or addressed in a new form.

The Laser Interferometer Space Antenna (LISA): LISA is a low-frequency gravitational wave observatory to complement higher-frequency Earth-based observatories like LIGO for studying black holes and making precision tests of general relativity. NASA has agreed to partner with the European Space Agency on an ESA-led space-based gravitational wave observatory. NASA is currently investing in technology development to enable a significant role for the US community. While participation in LISA as envisioned in *NWNH* was not possible in the early part of this decade, this new plan as of 2016 for participation in LISA is responsive to the recommendations of *NWNH-AMA*.

The International X-ray Observatory (IXO): IXO is a major new X-ray telescope for studies of the high-energy Universe. NASA has agreed to partner with the European Space Agency in the ESA-led Athena X-ray observatory. NASA will be providing contributions to both instruments as well as the observatory. US scientists are participating as leaders and members of the ESA study science team, the instrument consortia, and the science working groups. While IXO as originally envisioned in *NWNH* is not happening as a US-led project, the involvement in Athena that has developed in the past three years will enable US involvement in this science. This plan was endorsed by *NWNH-AMA*.

Finding: The science priorities envisaged by *NWNH* as being addressed by LISA and IXO are beginning to be addressed by recent engagement by NASA in LISA and the ESA-led Athena X-ray observatory.

4.1.2 Ground-based Projects

The programs and initiatives discussed in this section are roughly ordered, although not rigidly, in reverse anticipated order of completion. Ongoing programs or missions that were highlights of past decadal surveys are included when the AAAC believed they are either still scientifically particularly relevant to the developing new initiatives (that is they provide context) or impact the availability of funding for new initiatives. The projects, facilities, or programs discussed in this section are all in progress or active. Those that are recommended, but upon which work has not begun are discussed in section 4.2.

Large Synoptic Survey Telescope (LSST): LSST is a wide-field imaging optical observatory targeting all three *NWNH* science themes. Researchers will use LSST data products to probe

the fundamental natures of dark energy and dark matter, study the constituents of our Solar System, map and understand the structure and contents of the Milky Way Galaxy, and survey the transient sky. The highest ranked ground-based program of *NWNH,* and the highest priority for the DOE-HEP Cosmic Frontier in the 2014 P5 strategic plan, this project moved into the construction phase and the camera received DOE Critical Decision 3 (CD-3), start of full construction, in August 2015. The NSF funded part of the project is now more than 33% complete and the DOE funded LSST camera is more than 50% complete. An innovative partnership in the construction of a major research facility, combining the resources of private philanthropic donors and the federal government, the LSST survey should begin in 2022. Of the large ground-based projects recommended by *NWNH*, the NSF, in collaboration with DOE, has made the most substantial progress on LSST.

Finding: The AAAC is gratified to see the substantial progress toward the highest priority decadal ground-based facility, LSST, which is advancing toward the start of survey science operations in 2022.

Mid-Scale Innovations Program (MSIP)*:* As another priority for large-ground based programs, *NWNH* recommended the introduction of a competed grant program at the NSF for a broad range of possible mid-scale projects beyond the scope, either in budget or intent, of the Astronomy and Astrophysics Grants (AAG) program, the Major Research Instrumentation (MRI) program, the Advanced Technologies and Instrumentation (ATI) program, and the Major Research Equipment and Facilities (MREFC) program. In response, NSF/AST initiated the Mid-Scale Innovations Program (MSIP) in 2014 to fund medium scale projects which are too small to be funded by the MREFC line but too large for individual grants. The first call for proposals solicited projects in the cost range $4-40M. The second call was for projects in the range $4-30M. Those proposals seeking financial support in return for providing open access to a facility could ask for less than $4M. The allowed scope of proposed targets for support is also broader than those of MRI, ATI, or the former Telescope System Instrumentation Program (TSIP) or University Radio Observatory (URO) program. *NWNH-AMA* noted that during the first two MSIP rounds of this decade, NSF has funded some exciting science, for a total of fourteen projects in the $2-11M award range. *NWNH-AMA* found that, “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.” Funding levels remain lower than envisaged in *NWNH.*

Finding: The AAAC applauds the efforts by NSF/AST to develop, sustain, and expand the Mid-Scale Innovations Program.

Recommendation: The AAAC continues to support NSF/AST’s efforts to grow and develop the MSIP program, provided this is done while maintaining a balanced portfolio of investments by NSF/AST.

DESI: The *Dark Energy Spectroscopic Instrument (DESI)* is a DOE HEP-led project with contributions from NSF/AST, universities, private foundations and international agencies. DOE is providing a new, next-generation spectrograph and related instrumentation and computing systems. Installation will start in 2018 onto the Mayall 4-m telescope at Kitt Peak National Observatory in Arizona, operated by AURA/NOAO on behalf of the NSF. In 2014, P5 encouraged DOE-HEP to support DESI as part of its broad-based dark energy program. DOE/HEP and NSF/AST have recently signed an MOU (June 2015) for jointly supporting operations of the Mayall 4m telescope in FY 2016 through FY 2018, for preparatory work and start of installation of the spectrograph on the Mayall telescope. The agreement for the operations phase, in which DOE/HEP is going to fully support the operations of the Mayall telescope and computing systems during the data-taking phase, is still in development. DESI received CD-3 by DOE in June 2016.

Daniel K. Inouye Solar Telescope (DKIST)**:** *DKIST*, known during development as the Advanced Technology Solar Telescope, was awarded American Recovery and Reinvestment Act funding as part of the MREFC line of NSF in FY 2009. DKIST is a 4.2 meter solar telescope located at the Haleakala Observatory in Hawaii and is proceeding for a 2020 completion date. The primary mirror was completed at the University of Arizona in December 2015 and the enclosure components are on site with construction nearing completion.

LIGO: Advanced LIGO, the ground-based gravitational wave experiment, started science operations on September 12, 2015. On September 14, 2015, LIGO achieved the first direct detection of gravitational waves, from a merging binary pair of black holes of 29 and 36 solar masses. This was named the 2016 Breakthrough Discovery by *Science*.

Dark Energy Survey (DES): DES, recommended as a DOE priority in the 2007 P5 report, is an international project jointly funded by DOE, NSF, universities and international agencies to conduct a large imaging survey to probe dark energy and the origin of cosmic acceleration. The DOE is responsible for the Dark Energy Camera (DECam). DECam is mounted on the Blanco 4-meter telescope at CTIO, which is operated by NOAO (NSF). Having just finished its fourth observing season, DES will soon release cosmological measurements and constraints from the year 1 data followed by results from the year 1-3 data sample later this year.

Dark Matter: Understanding and identifying the nature of dark matter is a priority of both P5 and *NWNH* reports and both laboratory and astrophysics experiments/investigations will be needed. *NWNH* identified understanding the nature of dark matter as a science frontier question for advancing knowledge, underscoring the need for both direct detection and indirect detection. P5 stressed the complementary approach combining direct detection of dark matter,

indirect detection, and accelerator searches. Three G2 direct detection dark matter experiments were selected for development in June 2014 by DOE/HEP and NSF/PHY. Two experiments, Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Lab (SuperCDMS-SNOLAB) and LUX-Zeplin (LZ) search for weakly interacting massive particles (WIMPs), and the Axion Dark Matter eXperiment Generation 2 (ADMX-G2) is sensitive to axions. DOE HEP is supporting the fabrication and operations of LZ and ADMX-G2; DOE HEP and NSF/PHY are supporting fabrication and operations of SuperCDMS-SNOLAB. All projects are moving forward and LZ had CD-3 by DOE in January. ADMX-G2 started operations in its first frequency range in January 2017.

Cosmic Microwave Background: Commissioning of the 3rd generation South Pole Telescope (SPT-3G) instrument has been completed and operations are starting. *NWNH* supported the development of CMB research and cited interagency coordination as being important for a successful implementation of a coherent ground-based Stage-4 CMB project (CMB-S4). Participation in CMB science through the development of CMB-S4 in the next decade has been endorsed by P5. DOE, NSF and NASA have a long history in supporting CMB research and this area serves as a model for interagency coordination. At the request of DOE HEP, NSF/AST, NSF/PHY and NSF/OPP the AAAC has established a sub-panel entitled “The Cosmic Microwave Background Stage 4 Concept Definition Task Force” (CDT) to lay out science and technical requirements and develop a strawman concept for a CMB-S4 experiment, including the layout of science and technical requirements. More information about the creation of the CDT is provided in section 5.

ALMA: The Atacama Large Millimeter/submillimeter Array (ALMA), or its precursor proposed concept, was a priority of the 1990 decadal survey that was reaffirmed in the 2000 decadal survey, *Astronomy and Astrophysics in the New Millennium*. It was undertaken as a joint project between the NSF, ESO, and NAOJ. The facility was inaugurated in March 2013 and is nearing full capability. Cycle 4 observing began in fall, 2016, and the Cycle 5 deadline is in March 2017. Science highlights include the imaging of planet formation in gas and dust emission in HD163296, and the detection of the snow line in the circumstellar disk around the young star FU Ori. *NWNH-AMA* noted the completion during this decade of some of the projects of the previous decadal survey, including ALMA, which is enabling transformational science in the submillimeter.

Very Large Array (VLA): With traceable roots back to at least the report *Ground-Based Astronomy: A Ten-Year Program*[25] (A. E. Whitford, 1964) and recommended by the following decadal survey report, the 1972 *Astronomy and Astrophysics in the 1970s*,[26] the *VLA* has enabled transformational science as a premiere radio telescope at centimeter wavelengths. Its combination of sensitivity and high angular resolution allow it to match the imaging capability of

[25] https://www.nap.edu/read/13212/chapter/1

[26] https://www.nap.edu/catalog/13231/astronomy-and-astrophysics-for-the-1970s-volume-1-report-of

ground-based OIR telescopes. An upgrade of the *VLA* was recommended by the 2001 decadal survey report *Astronomy and Astrophysics in the New Millennium,*[27] allowing as much as two orders of magnitude improvement in sensitivity over the previous array. The enhanced array has been renamed the *Karl G. Jansky Very Large Array (JVLA),* in honor of the pioneering radio astronomer.

4.1.3 Other Initiatives or Recommendations In Progress

NWNH made a series of additional recommendations regarding the health and future of the astronomy and astrophysics community and research that are in the process of being implemented or acted upon by the agencies, but did not fit naturally in the space-based (4.1.1) or ground-based (4.1.2) sections above. We assess progress and make necessary recommendations for these in this section. The programs and initiatives discussed in this section are roughly ordered, although not rigidly, in reverse anticipated order of completion. The logic behind the reverse ordering is that we begin with programs that are most at risk in a climate of budget uncertainty (or reduction). Ongoing programs or missions that were highlights of past decadal surveys are included when the AAAC believed they are either still scientifically particularly relevant to the developing new initiatives (that is they provide context) or impact the availability of funding for new initiatives. The projects, facilities, or programs discussed in this section are all in progress or active. Those that are recommended, but upon which work has not begun, are discussed in section 4.2.

Balanced NSF/AST Portfolio Investment: Multiple reports emphasize that NSF/AST should maintain a balanced investment across its portfolio of grants and facilities. NSF/AST has shown it understands these recommendations and has worked to take actions consistent with this guidance. When additional guidance has been needed to make specific challenging choices, NSF/AST has sought the detailed assessments it required. An example of such guidance is the commissioning of the PRC, its review of the portfolio, and its report in 2012. The formation of the PRC was recommended by *NWNH.* Since then NSF/AST has been working to act upon the recommendations of the PRC, but it is still dealing with a challenging balancing effort.

In 2016, the mid-decadal review conducted by the National Academies revisited the progress of the NSF toward achieving balance in its portfolio while dealing with the challenge of growing operations costs of facilities. As noted in *NWNH-AMA*, “The committee strongly supports the goal of a balanced program that includes facilities, mid-scale initiatives, and small-scale initiatives. Maintaining this balance is a challenge at the current level of funding.” This is particularly the case when LSST and DKIST operations begin. As a result, carrying out the recommendations of the 2012 Portfolio Review Committee (PRC) report for facility divestment continues to be a priority. Otherwise the recommended balance in supporting individual investigator grants, mid-scale initiatives, and facility operations will not be achievable.

[27] https://www.nap.edu/catalog/9839/astronomy-and-astrophysics-in-the-new-millennium

NWNH-AMA notes the increasing impact of the operations costs of large facilities on the ability to fund individual investigators. "The remarkable scientific progress of the first half of the decade was made possible by capital investment in the 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." The AAAC agrees with this motivation and concern.

However, it is recognized by the Portfolio Review Committee, NSF/AST, and the AAAC that complete removal of funding from a facility/telescope might remove productive and sometimes unique assets from being available for astronomical research. For this reason, the preferred divestment alternative being pursued by the NSF has involved forming partnerships that enable valuable observing capabilities (the combination of telescope and instrumentation) to be used for astronomical research. This approach could and should reduce costs to NSF/AST without as severe an impact (on research) as closure.

NSF/AST faces significant challenges in implementing the PRC report recommendations. Congress has asked to be kept fully apprised of potential facility closures. To fully achieve the goals of the PRC, it is important to minimize policy constraints that would impede cost effective reallocation of resources. The AAAC is concerned that the slow rate of implementation of the PRC report recommendations threatens the highest priority ground-based projects of *NWNH*, especially the funding of midscale opportunities and individual research grants that are so critical to realizing the goals of *NWNH*.

The NSF has undertaken engineering and baseline environmental surveys for a number of facilities in order to assess the feasibility of the following options: (1) new partnership agreements, (2) conversion to a new mission with scope reduction, (3) mothballing of facilities, (4) decommissioning. Below is a list of the affected facilities and their status.

- KPNO 2.1m: A Caltech-led consortium, Robo-AO, is operating this telescope for FY 2016-2018. This is an excellent example of NSF/AST keeping one of its facilities an active contributor to the US scientific enterprise while reducing the funds NSF/AST is spending in support of operating facilities.
- Mayall 4m: The DESI survey will use this telescope along with newly supplied multi-fiber spectrographs. While the telescope will be operated by NOAO, which is run by AURA, Inc., under a cooperative agreement with the NSF, the costs of operations of the telescope with the new spectrographs to carry out the survey will be borne by DOE. There is an MOU between the NSF and DOE regarding joint support for the operation of the Mayall 4m during the preparatory and installation phase for DESI. An MOU is in development regarding DOE's support for the Mayall 4m during DESI operations in the data-taking phase of the project.

- WIYN 3.5m: The University of Wisconsin, Indiana University, University of Missouri, and the National Optical Astronomy Observatory (on behalf of AURA for the NSF) comprise the consortium currently operating the WIYN 3.5m telescope on Kitt Peak. There is a 2015 MOA between NASA and NSF that created a partnership for the NASA-NSF Exoplanet Observational Research (NN-EXPLORE) program in which the NOAO time using the telescope is devoted to community exoplanet research. NASA is procuring and will commission an extreme precision Doppler spectrograph for WIYN. This new partnership between NASA and NSF addresses a science priority identified in *NWNH,* but does not reduce NSF/AST's costs in supporting this facility, which would be consistent with the recommendations of the PRC.
- Green Bank Observatory: The Environmental Impact Statement process was started for this facility in October 2016; a draft EIS is in preparation. There was a separation from NRAO, but not Associated Universities, Inc. (AUI), in October 2016. Operations partnerships are under development and consideration; non-NSF organizations are currently contributing 25% of the funds required to address/meet GBO basic scope operations.
- Long Baseline Observatory / Very Long Baseline Array (VLBA): There was a separation from NRAO, but not AUI, in October 2016, with an MOA in place with the US Navy to substantially share the operating cost of VLBA.
- McMath-Pierce Telescope: NSF/AST has not yet identified any partner opportunities, but approaches for this telescope are still under investigation.
- GONG/SOLIS: SOLIS has been moved off of Kitt Peak for upgrades, then moved to Boulder, CO for testing, with proposed eventual relocation to Big Bear Solar Observatory. GONG is being refurbished, and the NOAA will be sharing operations costs for GONG, with an interagency agreement with NOAA already signed.
- Sacramento Peak Telescope: A university consortium to operate this facility is under development. The NSF funded NMSU for the transition of operations to this consortium. The EIS process has started, and will be complete in 2018.
- Arecibo: The NSF GEO/AGS contributed $4.1M in FY16 toward the operation of Arecibo. A solicitation for partners with a substantial funding ramp-down from both NSF/AST and NSF GEO/AGS was issued in January 2017, with proposals due in April. The Environmental Impact Statement process is in progress and the draft EIS identifies the NSF preferred alternative to be the collaboration supported by the solicitation. No decisions have been made regarding the funding of Arecibo or the outcome of the EIS. A record of Decision is targeted for late 2017.
- SOAR: The status and future of NSF support will be reviewed after 2020.

Recommendation: The AAAC concurs with *NWNH-AMA* recommendation that the NSF facility divestment process be moved forward and that the agencies work to ensure that individual investigators are funded, in order to capitalize on and leverage the full

capabilities of the large projects that represent such important and substantial investments by the agencies.

Recommendation: The AAAC supports the NSF approach of working to divest facilities to partners or non-federal organizations that will continue to operate them as scientific facilities.

Recommendations from Optimizing the US Ground-based OIR Astronomy System:
The *OIR System Report*[28] presented seven prioritized recommendations. The recommendations from the report are beginning to be addressed by NSF/AST and the community. The *OIR System Report's* second priority recommendation was that NSF/AST should direct the National Optical Astronomy Observatory (NOAO) to administer an ongoing community-wide planning process to identify the critical OIR System capabilities needed in the near term to realize the decadal science priorities.

Consistent with starting to implement such an ongoing planning and coordinating process related to decadal survey identified science priorities, the NSF/AST asked NOAO and LSST to carry out a study of a subset of the *NWNH* science goals, specifically those enabled in part or entirely by LSST. Specifically, a representative group of scientists was charged with considering six to eight LSST enabled science cases, quantifying the needed OIR capabilities (besides LSST) to enable those science cases and identifying existing and planned resources that could be used to accomplish these science goals. In 2016, study groups were convened to carry out this study, resulting in a workshop and subsequent report funded by the Kavli Foundation - "*Maximizing Science in the Era of LSST: A Community-based Study of Needed US OIR Capabilities*".[29]

In the course of producing the *Maximizing Science in the Era of LSST* report, six specific science cases were considered in detail. The OIR capabilities needed to achieve science goals were classified as "Critical, Very Important, or Important". Critical capabilities were identified for more than one science case. Commonalities in the necessary OIR capabilities across those science cases were identified, resulting in a set of high-level summary recommendations classified as follows:

- Critical resources in need of a development path: "Develop or obtain access to a highly multiplexed, wide-field optical multi-object spectroscopic capability on an 8m-class telescope, preferably in the Southern Hemisphere." This is a high priority capability that has potentially a long lead-time and hence requires investigation as soon as possible. A number of options involving modifications of (or new access to) existing facilities were considered.
- Critical resources that have a development path:

[28] https://www.nap.edu/catalog/21722/optimizing-the-us-ground-based-optical-and-infrared-astronomy-system
[29] https://www.noao.edu/meetings/lsst-oir-study/

    - “Deploy a broad wavelength coverage, moderate-resolution (R = 2000 or larger) OIR spectrograph on Gemini South.” Gemini is currently negotiating a contract with Southwest Research Institute to build such an instrument; to be commissioned in 2022-2023.
    - “Ensure the development and early deployment of an alert broker, scalable to LSST.”
- Critical resources that exist today: “Support into the LSST era high-priority capabilities that are currently available.”
- Infrastructure resources and processes in need of timely development:
    - “Support OIR system infrastructure developments that enable efficient follow-up programs.”
    - “Study and prioritize needs for computing, software, and data resources.”
    - “Continue community planning and development.”

NSF/AST commented on this study during the October 2016 AAAC meeting. The AAAC looks forward to hearing in the coming year how NSF/AST, AURA, Gemini Observatory, and NOAO anticipate working with the community to implement the recommendations of both the *OIR System Report* and the *Maximizing Science in the Era of LSST* report.

Finding: The AAAC notes and supports efforts by NOAO, the LSST Project, AURA, NSF/AST, and the Kavli Foundation to implement the recommendations of the *OIR System Report*, including efforts such as the well-executed engagement of the community that resulted in the *Maximizing Science in the Era of LSST* report.

Technology Development: Two medium-scale space-based programs in *NWNH* were focused on enabling technology: the higher priority of these involved technology for future extrasolar planet missions and the second involved technology for a potential next-decade cosmic microwave background mission to study the epoch of inflation. NASA has addressed the recommendation for technology development for extrasolar planet missions by funding starshade development and the WFIRST coronagraph. That is, technology development for exoplanet-related work on WFIRST is simultaneously responsive to this other *NWNH* recommendation.

4.2 Major Initiatives or Priorities Not Yet Started

While many of the goals and recommended new projects from *NWNH* have been taken up by the community with significant support from the agencies, some have not. Here we comment upon some of these recommended activities that have not yet garnered the support necessary to proceed. We also discuss, under spectral management and protection***,*** the possibility that while not currently an explicit priority of the reviews, it is an implicit priority that might need coordinated attention.

Giant Segmented Mirror Telescope (GSMT): GSMT is the generic description of a large optical and near-infrared telescope providing the next-generation spectroscopic infrared and optical facility in the 20-30 meter class. Two international consortia involving US universities or institutions are undertaking projects that could match what was recommended by *NWNH* as the GSMT. The Giant Magellan Telescope Observatory and the Thirty Meter Telescope are both starting construction. In 2012, the PRC Report recommended that NSF/AST invest in a GSMT only if the available funding for NSF/AST exceeded a threshold that has not been achieved; this recommendation was based on the need for program balance, discussed extensively above. In 2015, the *OIR System Report* reaffirmed that the NSF should plan for an investment in one or both of the GSMTs.

Atmospheric Čerenkov Telescope Array (ACTA): ACTA is a *NWNH*-recommended international instrument for high-energy gamma-ray astrophysics, aimed at answering questions about high-energy astrophysics and the fundamental nature of dark matter. The international Cherenkov Telescope Array (CTA) consortium is currently moving toward construction. The P5 strategic plan recommended to DOE HEP and NSF/PHY to "invest in CTA as part of the small projects portfolio if the critical NSF Astronomy funding can be obtained." CTA was the fourth ground-based priority in *NWNH*. Because of its funding constraints, NSF/AST informed the US CTA team that they would need to compete successfully in the MSIP program to receive AST funding. There has been little progress in realizing the *NWNH* recommendation of ACTA given the levels of available funding, higher ranked priorities, and the need to keep a balance of investment by the agencies.

Cerro Chajnantor Atacama Telescope (CCAT): The only recommendation of *NWNH* in the medium-sized ground-based project category was CCAT (formerly the Cornell-Caltech Atacama Telescope), a 25-m telescope with large-format cameras to enable surveys of the sky at submillimeter wavelengths and be a "finder-scope" for ALMA. *NWNH* suggested federal funding of about one-third of the costs, to be shared with university and international partners. The PRC reiterated its support for partial federal investment in CCAT, but since the remaining funding has not been identified, the NSF will consider future contributions to CCAT as part of a successful competition within the existing MSIP line.

Finding: The scientific justifications for the GSMT, ACTA, and CCAT continue to be strong and these projects are worthy of eventual support and participation by the federal government if funding opportunities become available to enable supporting one or more of these projects as part of a balanced program of investment by the agencies.

Recommendations from the US Ground-based OIR Astronomy System Report Not Yet Implemented: The OIR System Report recommendations that have not yet been implemented -- The OIR System Report included seven prioritized recommendations, most of which have not

yet been implemented, but are beginning to be discussed in the community, with NSF/AST, AURA, Gemini, LSST, and NOAO. Details regarding the to be acted upon recommendations can be found in the report and are the following: OISR(1) Creation of a telescope observing time/data exchange for OIR System observing capabilities; OISR(2) charge NOAO to set up an ongoing community planning process for recommending in detail the OIR system observing capabilities that need to be sustained or developed to enable decadal survey science priorities (the Kavli supported LSST and NOAO sponsored workshop and report, *Maximizing Science in the Era of LSST,* discussed above is an example of the type of efforts that can address this recommendation); OISR(3) NSF should support the development of a wide-field highly multiplexed spectroscopic capability on a medium or large aperture telescope in the southern hemisphere to enable a wide variety of science, including spectroscopic follow-up in support of the LSST science cases; OISR(4) a series of four specific recommendations for supporting and expanding upon LSST science cases; OISR(5), that the NSF should plan for an investment in one or both of the GSMTs; OISR(6) the NSF should continue to invest in the development of critical instrument technologies, including detectors, adaptive/active optics, and precision radial velocity measurements; OISR(7) NSF should support a coordinated suite of schools, workshops and training networks, run by experts, to train the future generation of astronomers and maintain instrumentation, software and data analysis expertise.

Recommendation: The AAAC supports efforts by AURA, NOAO, LSST, and NSF to implement the recommendations of the *OIR System Report*. We acknowledge that implementation of these recommendations will be constrained by the need to maintain a balanced investment across the portfolio of NSF/AST.

Spectral Protection and Management: Astronomical sciences are fundamentally dependent on the detection of light across the full range of the electromagnetic spectrum (EMS). The process through which portions of the EMS are protected or allocated for specific uses is understandably subject to a variety of scientific, economic, and security concerns and a large number of stakeholders whose interests need to be addressed. Both the NSF and NASA have staff assigned to spectrum management, and the National Academies sponsor the “Committee on Radio Frequencies” (CORF).

As commercial needs for access to the EMS increase (including more than a dozen new frequency requests from commercial interests to be considered at the 2019 ITU meeting), we are concerned whether the available NASA and NSF resources will be adequate to advocate for the protection of astronomical requirements on wavelength allocation. Without clean access to these wavelengths, the ability of astronomers to obtain fundamental knowledge about the universe would be profoundly impaired.

Finding: Increasing demand from scientific, commercial, and security interests for access to the same regions of the electromagnetic spectrum as those needed for

astronomical research pose a challenge for managing spectrum access and ensuring astronomical research continues to be viable in necessary regions of the EMS.

Recommendation: The agencies should consider coordinating their separate efforts on advising on the use and protection of the electromagnetic spectrum to better protect access to the electromagnetic spectrum for astronomical and astrophysical research.

4.3 Summary and Recommendations

NSF, DOE, and NASA all face budgetary constraints that make realizing the full scope of the community's aspirations challenging. We emphasize the need to maintain a balanced investment (range of program scales and investment in individual investigator awards), in order to achieve our scientific vision while maintaining a community robust enough to sustain US leadership in the sciences in the coming decades.

Finding: The AAAC finds that the agencies have executed very efficiently the priorities of the decadal survey, given their budgetary constraints, with prioritization of projects that closely matches the intent of *NWNH*. The agencies make good use of supplemental reviews and standing advisory committees to inform their planning and decision-making.

5. Preparation for 2020 Decadal Survey

Planning has begun for the next decadal survey of astronomy and astrophysics. The survey process is a lengthy one, typically two years in execution, and involving broad community participation. *NWNH-AMA* commented on many of the previous practices and has made recommendations to improve and streamline the survey process. Recommendations were also set forth in *The Space Science Decadal Surveys: Lessons Learned and Best Practices*[30] *(SSDS)*, with a focus on space projects.

NWNH-AMA recommends that the independent cost estimates for projects be retained. Cost estimates were new to the survey in 2010, as recommended by the 2008 NASA Authorization Act. The new recommendations include getting better estimates of cost and risk for ground-based projects and doing a fast, "cost-box" analysis for candidate missions, reserving the full cost ("CATE") analysis for the highest priority missions. *NWNH-AMA* also recommends a life-cycle cost analysis be routinely considered for ground-based facilities as it is for space-based missions.

Elements that *NWNH-AMA* feels need more attention in the 2020 survey are the inclusion of funding partnerships outside the federal agencies. International partnerships are becoming increasingly important in funding very large projects, but these partnerships rely heavily on the trust that reliable funding streams from the US will be sustained. Although international ties were strained in 2010 when NASA withdrew from IXO and LISA, the recent strong partnerships of NASA with ESA on Euclid, Athena, and the L3 gravitational wave observatory, and with JAXA on the X-ray Astronomy Recovery Mission (XARM), indicate that international ties have been strengthened in recent years. *NWNH-AMA* recommends that these international partners be included in the planning process. In a similar manner they suggest that including private philanthropies in the planning process would be helpful.

In preparation for the next decadal survey, *NWNH-AMA* recommends a comprehensive survey of the state of the profession of astronomy and astrophysics. This was done in the previous survey but the results were not made public. *NWNH-AMA* also notes that the previous structure, in which Science Frontier Panels identified top science goals and the Project Prioritization Panel recommended projects, did not always produce findings that ultimately aligned with the final survey committee recommendations. *SSDS* notes that it is difficult to reconcile the top science questions with the ability of the current field to address these questions. *NWNH-AMA* recommends that this structure be reconsidered.

[30] https://www.nap.edu/catalog/21788/the-space-science-decadal-surveys-lessons-learned-and-best-practices

Both *NWNH-AMA* and *SSDS* recommend collecting input in advance of the survey in the form of white papers and advisory committee reports in a comprehensive fashion to assemble an archive to inform and streamline the 2020 survey.

The next decadal survey report will depend heavily on the preparatory work of many groups from the community, industry, and the agencies preparing well-thought-out mission concepts and science goals for the decades ahead[31] from which the decadal survey can draw and build their recommended plan for the coming decade.

The AAAC is playing a part in enabling such preparation through the creation of a taskforce to help inform how a Stage 4 CMB experiment would be carried out in the coming years. At the request of DOE HEP, NSF AST, PHY and OPP, the Chair of the AAAC has established a subcommittee, the Cosmic Microwave Background (CMB) Stage 4 Experiment Concept Definition Task force (CDT) to lay out the science and technical requirements and develop a strawman concept for implementing a ground-based CMB-S4 experiment. The CDT will take as input the community CMB-S4 Science Book and any further community information as appropriate, and will consider the global landscape of CMB experiments (including ground, balloons, and space). The Chair of the AAAC has charged the CDT to provide a progress report to the AAAC by June 2017 and a final report to AAAC by October 2017 for consideration and approval. In accordance with Federal Advisory Committee Act (FACA) rules, this report will be discussed and approved by the AAAC before formal transmittal to the agencies.

The main focus of the CDT report is to outline a path to achieving the science goals of CMB-S4, as defined by community input (e.g., the CMB-S4 Science Book and further inputs). The adopted science goals can be used to define science objectives and requirements, which will be translated to technical requirements needed to achieve the science goals in the actual experiment. Other goals include defining how NSF and DOE can work together in order to ensure the continuation of stage 3 experiments and how they fit into agency priorities. The P5 report emphasized the importance of a DOE role in future experiments aimed at measuring detailed properties of the cosmic microwave background, advocating that work toward the next generation ground-based CMB experiment should become part of the DOE planning portfolio.

The CDT, chaired by Dr. Charles Lawrence of NASA/JPL, consists of leading members of the majority of ongoing (so-called "Stage 2 and 3") cosmic microwave background experiments, agency officials, community members invited for particular sessions, and support staff. Two members of the AAAC, including the chair, serve as liaisons with the CDT. The CDT has an external Advisory Board that includes one AAAC member.

Finding: The CMB-S4 CDT, a subcommittee of the AAAC created at the request of DOE and NSF, is carrying out a valuable process of determining science and technical

[31] An example is the 2013 NASA Astrophysics Roadmap, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013.pdf

requirements to meet the CMB-S4 science goals and to develop a concept, including the technical and mission requirements, for a ground-based CMB-S4 experiment.

There are many examples of thoughtful preparation for the decadal survey in progress.

In 2016, NASA assembled four Science and Technology Definition Teams to develop four large mission concepts: Origins Space Telescope (formerly Far IR Surveyor), Habitable Exoplanet Imaging Mission, Large UV/Optical Surveyor, and Lynx (formerly X-ray Surveyor), as input to the 2020 decadal survey. NASA is initiating 5-8 medium-size Astrophysics Probe mission concept studies in 2017. These studies will be valuable resources for the decadal survey committee as they consider priorities for the coming decade.

The National Radio Astronomy Observatory has been holding a series of conferences for future radio-millimeter-submillimeter science in the areas of Cradle of Life, Formation/Evolution of Galaxies, Fundamental Physics, and Cosmology and Cosmic Dawn, to gather community input in preparation for the 2020 survey.

Another example of a forward-looking effort towards the next decade is the Cosmic Visions dark energy group. Formed by the DOE's Office of High Energy Physics in August 2015 as a two-way communication group with the HEP-supported dark energy community, with a goal of investigating science directions, and experimental needs and opportunities to enhance, complement, or go beyond the already-planned Stage IV dark energy experiments supported by the DOE (DESI and LSST). Two other Cosmic Visions groups (on CMB and Dark Matter) also provide a communication path between the HEP community and the DOE HEP in these areas, but are at different stages of the process. Currently the Cosmic Visions dark energy group is building strong community support and developing science cases, with a goal of producing a Science Book in 1-2 years from now.

Another example of NASA engagement with the community that will help to inform science and mission planning for the future includes NASA's use of three Program Analysis Groups (PAGs) covering cosmic origins, physics of the cosmos, and exoplanets.

Finding: There is broad participation by members of the astronomy and astrophysics community, with agency support, in developing ideas for future experiments, missions, and programs to be undertaken in the coming decades, with the goal of producing well developed and well costed ideas and concepts to be considered by the 2020 decadal survey.

Recommendation: The AAAC supports the continued exploration, with the support of the agencies, into future directions and experiments, missions, and programs to be considered for support by the 2020 decadal survey.

The current timetable is to have the next decadal survey proposal into the funding agencies by spring 2018, with an anticipated survey finish date of December 2020.

Recommendation: The AAAC recommends that the agencies work with the National Academies to ensure a timely beginning to the next decadal survey, along with updates to the structure as recommended by *NWNH-AMA*.

6. Budget Summary and Impact

This year is widely acknowledged as one of the most uncertain budget situations in recent history. The Continuing Resolution for FY 2017 is in place until April 28 and further action will be needed by Congress to provide spending authority for the remainder of the year. At the same time, the new Administration is in the process of developing a FY 2018 budget proposal. Full details with specific impacts on Executive Branch agencies may not be available until later in the calendar year. For the time being, NASA, NSF and DOE will be operating under a continuing resolution that will sustain the current programs.

The pending FY 2017 budget is significant for NASA. Both the House and Senate had acted to restore discretionary spending authority that had been identified in the Administration's request as mandatory funding. Loss of this spending authority would have resulted in a 4.7% reduction in astrophysics. Of the $85 million in proposed mandatory spending, $76 million was associated with *WFIRST*. The actions of the Congress will keep *WFIRST* on track and sustain all essential programs if the final funding action after the expiration of the current Continuing Resolution upholds these proposals.

The AAAC has paid special attention to the major efforts underway within NSF, NASA and DOE and their need for budget stability. Flight programs within NASA, and construction programs being carried out by NSF and DOE, are planned on multi-year time scales and depend on reliable judgments as to whether out-year budgets will provide the necessary program funding and contingency levels. Efficient and cost-effective management of these high-value contracts requires a high degree of budget certainty. The AAAC urges Congress and the agencies to establish guidance that will minimize the disruption in ongoing operations and major project cost and schedules.

Finding: Major flight and construction programs may be harmed by continued uncertainty in the budget, leading to cost overruns and schedule slips. The AAAC urges that special attention be paid to these programs at the time that the FY 2017 budget is finalized and the FY 2018 budget is formulated.

The AAAC was mindful of the potential range of impacts that the FY 2018 budget might have. Although the magnitude of budget reductions for NASA, NSF, and DOE is not known at this time, there will be a need to re-assess portfolio balance as these actions are taken. The AAAC believes that maintaining a viable grants program and sustaining the highest priority decadal survey initiatives should guide the agencies. DOE HEP has stressed that they fund university and lab scientists who have roles in their experiments, rather than funding individual investigator programs. Because of this different funding model, we exclude them from the following recommendation, but we encourage DOE to continue to fund the researchers located across the

community who are engaged in the design, construction, and operations of their experiments.

Recommendation: In formulating their programs for FY 2018, NSF, NASA and DOE should strive to maintain viable research grant programs and preserve the highest priority decadal survey recommended programs.

In addition to major construction and flight programs, one key issue of concern to the community is ensuring adequate and reliable grant funding, which sustains researchers, including students and post-doctoral researchers. A general priority of the last decadal survey, *New Worlds, New Horizons (NWNH)*, was the restoration and then maintenance of a balanced astronomy and astrophysics portfolio. The mid-decadal report similarly "stressed the importance of executing a balanced research program." For this reason *NWNH* suggested expanded support for individual investigator grants and research grant programs.

The AAAC has monitored the ongoing effort to reduce the oversubscription rate for grant funding, which has resulted in success rates as low as 16% for the individual investigator programs in NSF/AST and NASA. In last year's report the committee stressed the negative impacts of declining proposal success rates on the field. The declining success rates are a direct consequence of flat funding of the core program and the increased number of proposals being submitted due to an increasing number of proposers, and likely an increase in multiple submissions and resubmissions. The Principle Investigators submitting proposals remain a relatively stable demographic in terms of race, gender, number of years since PhD, and type of institution.

While the quality of submitted proposals remains high, an increasing fraction of meritorious proposals can no longer be funded, imperiling a vibrant program that attracts the brightest young researchers into the field. The AAAC has previously encouraged innovative management actions. This year a number of revisions to the proposal systems were presented to the AAAC.

Finding: The AAAC commends NSF/AST and NASA for devising and implementing plans aimed at reducing proposal pressure.

The NSF is experimenting with a “no proposal deadline” for its Solar and Planetary research Grants (SPG) program. Researchers will be able to propose at any time, and proposals will be reviewed once the number submitted exceeds a threshold. Depending on the results of this pilot program in a two-year period, the “no proposal deadline” option may be extended to the rest of the Astronomy & Astrophysics Grant Program.

NASA is to shift its Astrophysics Theory Program call for proposals to every other year (unlike the current annual solicitation). The proposal is to keep the total funded number of proposals constant in a two-year period, but reduce the frequency of review of non-competitive proposals in what NASA reports is a particularly over-subscribed area. While recognizing the motivators,

the committee feel this presents the risk that theory research, which broadens and informs the science goals of NASA missions, will not be timely. The two year cycle may also represent a risk for pre-tenure faculty members, who are often expected to secure funding within their first two years (in advance of a review for renewal in their third year). While theory proposals will continue to be submittable on an annual basis to NSF, the focus and emphasis of the proposed research will be different, and it is not clear to the committee whether or not the available NSF opportunities, which are also heavily oversubscribed, can mitigate the impact of this change in the NASA ATP frequency of solicitation.

NASA also plans to reduce the number of prize postdoctoral fellowships by 25%, while streamlining the application process for further cost savings. The AAAC understands the concern raised by NASA over the number of prize fellowships offered each year as NASA responds to recommendations to have a balanced portfolio. NASA intends to balance the fellowship funding with respect to funding research grants, which are under significant strain. While supportive of the plan, the committee feels it is important that this redistribution be achieved in such a way that individual subfields are not disproportionately impacted. For example, if theorists tend to be overrepresented amongst fellowship recipients, the AAAC recommends that care is taken to ensure that this does not lead to a net reduction in theory funding by NASA.

Recommendation: The committee recommends that NASA carefully monitor the impact of the planned changes to the prize fellowship and ATP solicitations (reduction in the number of prize fellowships offered annually and change in the frequency of ATP solicitations to every other year) to ensure that specific subfields within astronomy and astrophysics, such as theory, are not disproportionately affected.

The AAAC has also encouraged the continued efforts identified in the NSF Portfolio Review to divest those lower priority facilities and those that can plausibly be supported by non-NSF sources. In 2015 the AAAC found “A very low proposal success rate impacts both researchers and the agencies. Researchers spend more time resubmitting meritorious but unfunded proposals and serving on review panels. Some researchers may elect to leave the field or decide not to pursue original and potentially transformative research. Agencies must manage the increased workload, staffing problems, and increased costs associated with reviewing more proposals." In addition, the mid-decadal survey report observed that “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." And that “...Even following the divestment recommended by the Portfolio Review, the operations costs of ALMA, DKIST, and LSST will compromise the ability of the US 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."

The AAAC 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.” 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. 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.

Finding: At current budget levels the anticipated facilities operations costs are not consistent with a program balance that ensures scientific productivity. Conversely, even moderate increases in the NSF-AST grants budget would have a highly leveraged impact. The AAAC recognizes that this need will be even more difficult to fulfill if major budget reductions in FY 2017 and beyond materialize.

Appendix A: Explanation of Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
AAG	Astronomy and Astrophysics Grant
AAS	American Astronomical Society
ACTA (or CTA)	Atmospheric Čerenkov Telescope Array
ALMA	Atacama Large Millimeter/submillimeter Array
ATI	Advanced Technologies and Instrumentation
AUI	Associated Universities, Inc.
AURA	Association of Universities for Research in Astronomy, Inc.
ADMX	Axion Dark Matter eXperiment
CAA	Committee on Astronomy and Astrophysics
CD	Critical Design review
CDT	Concept Definition Task Force
CMB	Cosmic Microwave Background Radiation
CTA (or ACTA)	Atmospheric Čerenkov Telescope Array
DECam	Dark Energy Camera
DES	Dark Energy Survey
DESI	Dark Energy Spectroscopic Instrument
DKIST	Daniel K. Inouye Solar Telescope
DOE	Department of Energy
DOE/CF	Department of Energy High Energy Physics Cosmic Frontier
EIS	Environmental Impact Statement
EMS	Electro Magnetic Spectrum
ESA	European Space Agency
ESO	European Southern Observatory
FACA	Federal Advisory Committee Act
FDR	Final Design Review
FY	Fiscal Year
GEO/AGS	Geosciences Directorate/Division of Atmospheric and Geospace Sciences
GONG	Global Oscillation Network Group
GSMT	Giant Segmented Mirror Telescope
HCT	Himalayan Chandra Telescope
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel
HST	Hubble Space Telescope
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
KPNO	Kitt Peak National Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory

LISA	Laser Interferometer Space Antenna
LSST	Large Synoptic Survey Telescope
LZ	LUX-Zeplin
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MPS	Mathematical & Physical Sciences (NSF Directorate for …)
MREFC	Major Research Equipment and Facilities
MRI	Major Research Instrumentation
MSIP	Mid-Scale Innovation Program
NAOJ	National Astronomy Observatory of Japan
NASA	National Aeronautics and Space Administration
NASA/APD	National Aeronautics and Space Administration Astrophysics Division
NEID	NN-explore Exoplanet Investigations with Doppler spectroscopy
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NSB	National Science Board
NRC	National Research Council
NSF	National Science Foundation
NSF/AST	National Science Foundation Division of Astronomical Sciences
NSF/OPP	National Science Foundation Office of Polar Programs
NSF/PHY	National Science Foundation Division of Physics
NuSTAR	Nuclear Spectroscopic Telescope Array
NWNH	The 2010 NRC decadal survey report "*New Worlds, New Horizons in Astronomy and Astrophysics*"
NWNH-AMA	The 2016 NRC mid term assessment report, "*New Worlds, New Horizons in Astronomy and Astrophysics, A Midterm Assessment"*
OHEP	Office of High Energy Physics, DOE
OIR	Optical InfRared
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
P5	Particle Physics Project Prioritization Panel
PRC	National Science Foundation Portfolio Review Committee
R&D	Research and Development
SDSS	Sloan Digital Sky Survey
SMD	Science Mission Directorate, NASA
SOAR	SOuthern Astrophysical Research Telescope
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOLIS	Synoptic Optical Long-term Investigations of the Sun
SPT	South Pole Telescope
STEM	Science, Technology, Engineering and Math
Super CDMS	Super Cryogenic Dark Matter Search

TAG	Tri-Agency Group
TESS	Transiting Exoplanet Survey Satellite
TSIP	Telescope System Instrumentation Program
UKIRT	UK Infrared Telescope
URO	University Radio Observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLT	Very Large Telescope
WFIRST	Wide-Field Infrared Survey Telescope
WIMPS	Weakly Interacting Massive ParticleS
XARM	X-ray Astronomy Recovery Mission
XRP	Exoplanet Research Program