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COLLEGE OF SCIENCE
Astronomy
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March 15, 2018

Dr. France A. Córdova, Director
National Science Foundation
2415 Eisenhower Avenue, Suite 19000
Alexandria, VA 22314

Mr. Robert M. Lightfoot, Jr., 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 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 fifteenth 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 pleased and honored 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 Markey, Ranking Member, Subcommittee on Space, Science, and Competitiveness, Committee on Commerce, Science and Transportation, United States Senate
Dr. Joan Ferrini-Mundy, Chief Operating Officer, Office of the Director, National Science Foundation
Dr. James Ulvestad, Chief Officer for Research Facilities, Office of the Director, National Science Foundation
Dr. Anne Kinney, 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. Yi Pei, 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. Deborah Lockhart, Deputy Assistant Director, Directorate for Mathematical and Physical Sciences, National Science Foundation
Dr. Richard Green, Division Director, Division of Astronomical Sciences, National Science Foundation

- Dr. Ralph Gaume, 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. Buell 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. Eliza Kempton, University of Maryland
- Dr. Shane Larson, Northwestern University
- Dr. Rachel Mandelbaum, Carnegie-Mellon University (Vice Chair)
- Dr. John O’Meara, St. Michaels College
- Dr. Constance Rockosi, University of California, Santa Cruz
- Dr. William Smith, ScienceWorks International
- Dr. Martin White, University of California, Berkeley

Report of the Astronomy and Astrophysics Advisory Committee

March 15, 2018

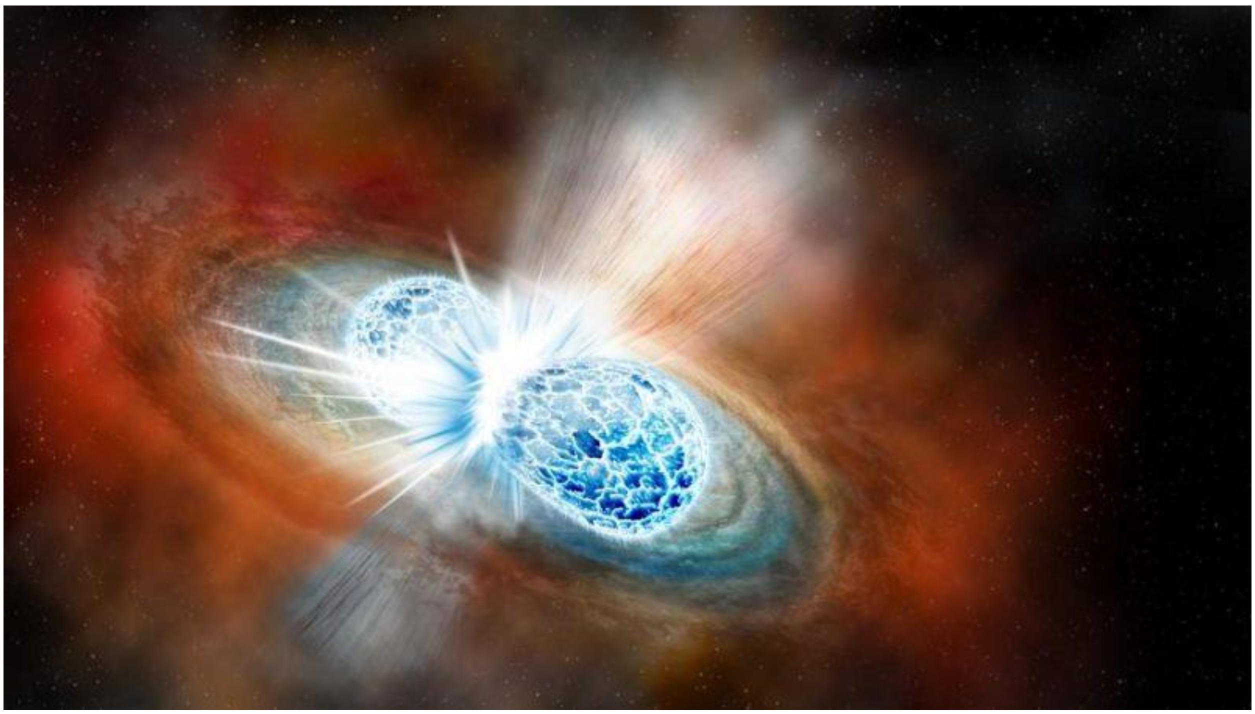

Image credit: Robin Dienel courtesy of the Carnegie Institution of Science.

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The cover photo of this report is an artist's illustration of one of the research highlights of 2017, the observation of the merger of two neutron stars. Image credit: Robin Dienel courtesy of the Carnegie Institution of Science.

Executive Summary

Significant and sustained investment by the US Government and the American people in basic astronomy and astrophysics research furthers our understanding of the Universe. Concurrent investment in the technological innovations and well-educated workforce that are required to undertake our ambitious endeavors will, like our past investment in LIGO,[1] help sustain US leadership in science and technology. These investments in turn yield broad economic benefits for our country.[2]

The Astronomy and Astrophysics Advisory Committee (AAAC) commends the NSF, NASA, and DOE for their successful efforts to provide balanced and coordinated investments in basic research and the world leading facilities and missions that further the priorities of *New Worlds, New Horizons in Astronomy and Astrophysics (NWNH),* the most recent decadal survey of the National Research Council (NRC) of the National Academies. As we approach the start of the next decadal survey, we are seeing tremendous return on the past investments by the federal government, with major results including the first direct detection of an electromagnetic counterpart of a gravitational wave source; the birth of multi-messenger astronomy.

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 continuing 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 the 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 continuation of the funding of the Wide Field Infrared Survey Telescope (WFIRST) in FY 2019 and beyond.

We list our complete set of 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.

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[1] Laser Interferometer Gravitational-Wave Observatory

[2] 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 2.1

Finding: The staff of the Arecibo observatory, which was a federally funded facility during 2017, carried out a variety of critical public services in the aftermath of Hurricane Maria that were of great value to the broader community in Puerto Rico. The AAAC commends and extends our gratitude to the Arecibo staff for their efforts to aid their community and prevent additional loss of life.

Finding: The outreach and educational efforts of the astronomical community related to the Great American Eclipse of 2017, as supported by many including the NSF and NASA, were highly successful in developing scientific engagement among the public.

Section 2.2

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 and outreach efforts. Coordination between the agencies was particularly important and valuable in enabling these discoveries.

Section 3.1

Finding: NSF, DOE, and NASA continue to work 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.

Section 3.2

Finding: Astronomical surveys and major astrophysical simulations (for example, but not limited to, cosmological simulations) have broader and greater impact if in addition to the generation of high quality data sets and clear presentation of their results, the data and derived data products are made public along with appropriate tools to access the data products. When the software used to generate the data and data products is also publicly available, it is more straightforward for other researchers to produce new scientific results with the dataset, as well as to reproduce and verify previously-reported scientific results.

Finding: Public data releases, including data access tools, software used to generate the data and data products, and documentation of the data, software, and access tools, are quite costly and deserve curation in order to realize the potential of increased long-term impact of such availability of the data sets and related materials.

Recommendation: All current and planned surveys should publicly release their data with suitable access tools and documentation. This is consistent with the AAAC Principles of Access recommended by the AAAC in their 2013-2014 annual report. In addition, the surveys should release the source code used to create the data products. Surveys supported in part or entirely by the federal government through its agencies should work to include funding enabling adequate public access to the data, software, and data products produced through these surveys.

Recommendation: The three agencies should coordinate, and where possible standardize, the guidelines and expectations for the releases of data sets, data products, data access tools, and related software used to produce future surveys, astrophysical simulations, and missions. The goal of this coordination should be to help researchers efficiently provide access to the data they produce through tools useful for the broad scientific community with minimal duplication of effort between agencies and stakeholder groups. Release and documentation of the software used to generate and analyze the data will enhance the quality of current and future science by enabling more cost effective reproducibility and extension of the scientific results from the initial studies.

Finding: The tri-agency and tri-project groups have conducted useful investigations to explore coordination between science teams planning to use LSST and Euclid to further the study of dark energy.

Recommendation: We recommend that the three agencies either broaden the current discussions or create parallel discussions to consider broadly the costs and benefits of coordination on the science areas of interest to both the Euclid and LSST communities. We recognize that if a decision is made to plan for coordination between LSST and Euclid during construction of LSST and to execute such a plan during LSST operations, the budgets for both the construction and operation of LSST would likely need an augmentation.

Finding: The AAAC appreciates that the agencies are attempting to preserve a balanced portfolio in the face of significant budget pressure and realize the goal of keeping projects currently under construction on schedule and on budget.

Recommendation: The agencies should continue to prioritize a balanced portfolio, and in particular maintain a viable research and analysis program, using existing mechanisms familiar to the community such as the portfolio reviews and pacing of the early funding and review milestones for new projects. The agencies should communicate clearly with the community as these processes evolve to match the pressures on their programs.

Finding: The portfolio reviews and other processes for the assessment of current missions, projects, and facilities, are important tools for the agencies to maintain a balanced portfolio between new projects, operation funding for current facilities, missions and experiments, and research funding for science analysis and technology research and development. The AAAC is supportive of the agencies using the portfolio reviews to help maintain a balanced program.

Recommendation: The agencies should continue to communicate with each other about current and future portfolio reviews and consider how joint projects between agencies are meeting the priorities of all stakeholders.

Finding: The AAAC applauds the NSF and NASA for having supported the first steps into the exciting new field of multi-messenger astronomy. These initial results for multi-messenger astronomy are impressive achievements and are important examples of science benefiting from interagency coordination, combining LIGO, the Fermi satellite, IceCube, and many other space and ground-based facilities observing across the electromagnetic spectrum. Multi-messenger astronomy is clearly a well-stated priority of the NSF and is explicitly (NASA's support of space missions enabling this science as part of their science mission) and implicitly (DOE's partnership with NSF in projects and facilities that support the NSF's goals for this science) enabled by the other agencies.

Finding: The AAAC recognizes that NASA's space mission portfolio has great potential for supporting the emergent area of multi-messenger astronomy that has been opened by the NSF supported observations of gravitational waves and high energy particles, including neutrinos. The AAAC further recognizes that existing agency partnerships (e.g. between DOE and NSF for LSST) have the potential of further supporting the development of multi-messenger astronomy and astrophysics.

Recommendation: The AAAC supports an intensification by NSF and NASA of existing collaborations that support multi-messenger astronomy, inspiring a new generation of engineers and scientists to work in this emerging area.

Recommendation: The AAAC recommends that all three agencies, in recognition of the compelling science opportunities provided by the emerging field of multi-messenger astronomy, do their best to support the capabilities, facilities, missions, and programs on which progress in this area depends. For the NSF, multi-messenger astronomy is a well-recognized high priority. We recommend that DOE and NASA stay in close communication with NSF to avoid inadvertently hindering, through actions affecting their own programs or missions, this high priority of their partner agency.

Finding: Competing interests continue to provide a severe and unrelenting threat to astronomers' ability to detect emission originating outside of the terrestrial sphere. Without clean access to these wavelengths, the ability of astronomers to obtain fundamental knowledge about the universe is profoundly impaired.

Finding: The resources currently available to the NSF and NASA are not sufficient to protect essential astronomical wavelengths in an arena of competing commercial interests with deep financial support and professional lobbyists.

Recommendation: NASA and NSF should enhance their collaboration with each other and with other groups, including international agencies and commercial interests, to protect the accessibility of essential astronomical wavelengths to researchers.

Recommendation: Efforts, ideally coordinated with all three agencies, should be made to increase awareness of spectrum management issues among astronomers, the general public, and government agencies. Possible agents for meeting this recommendation might include the NSF-funded national facilities for operations at radio and optical wavelengths.

Section 4.1.1

Finding: NASA's Wide-Field Infrared Survey Telescope (WFIRST), following either path described in the NASA Associate Administrator Dr. Thomas Zurbuchen's memo of October 2017, would deliver the science identified for the version of WFIRST recommended in *NWNH:* dark energy, exoplanets, and galaxy evolution.

Finding: A NASA Wide-Field Infrared Survey Telescope (WFIRST) that retains the 2.4m telescope, a wide-field instrument, and a coronagraph would deliver the science identified for the version of WFIRST recommended in *NWNH* and provide a technology demonstrator for future coronagraphic imaging missions.

Recommendation: The AAAC supports the recommendations of the 2017 WFIRST Independent External Technical/Management/Cost Review (*WIETR)* report and the subsequent process implemented by the NASA Associate Administrator in October of 2017 for realizing the science that would be delivered through the *Wide-Field Infrared Survey Telescope*. The AAAC agrees with the need to maintain cost containment for the WFIRST mission, and supports a rigorous cost assessment and mission review prior to WFIRST entering Phase B.

Finding: The President's requested level of FY 2019 funding for NASA's Astrophysics division is not large enough to enable both a balanced portfolio of investments in Astrophysics and the funding for NASA's Wide-Field Infrared Survey Telescope (WFIRST).

Finding: The proposed termination of WFIRST, as presented in the President's requested FY 2019 budget for the astrophysics division of NASA, would result in the withdrawal of federal support for the highest ranked priority for space from *NWNH.*

Finding: A balanced investment by NASA in astrophysical research, including a mix of major, medium, small, and individual research awards, is recognized by the AAAC as the preferred path for NASA to maximize its impact in astrophysical research.

Finding: The AAAC strongly supports the federal government respecting the integrity and importance of the decadal survey process for identifying the priorities for the agencies engaged in supporting astronomical and astrophysical research.

Recommendation: In order to maintain a balanced investment in astrophysical research while continuing to support WFIRST, the highest ranked priority for NASA by the most recent decadal survey, *NWNH,* we recommend that the NASA budget be increased above the Presidents' request to allow a funding level for the astrophysics division that would enable the funding of WFIRST to continue in the context of a balanced portfolio of investment.

Finding: The AAAC supports the continued development of the US participation in LISA, following the guidance outlined in *NWNH-AMA.*

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 finds that with the planned Announcement of Opportunity for the Explorer program in 2019, the NASA Astrophysics Division is on target to meet *NWNH* and *NWNH-AMA* recommendations with respect to the number of Explorer program opportunities this decade.

Finding: The AAAC commends NASA and the extended team delivering JWST for their encouraging progress toward a 2019 launch of what will be the most powerful telescope ever launched into space.

Finding: The AAAC applauds the extended team working to deliver JWST for their successful efforts to complete the cryogenic tests during Hurricane Harvey in 2017.

Section 4.1.2

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

Recommendation: The AAAC urges NSF and DOE to put in place a long-term operations plan and research plan that will, while maintaining a balanced overall portfolio, ensure that the US science community can capitalize on the substantial investment in LSST.

Finding: The AAAC recognizes and applauds the efforts by NSF/AST to develop and sustain the Mid-Scale Innovations Program (MSIP). The scale and types of programs supportable by MSIP are challenging to realize through any other existing funding program.

Recommendation: NSF/AST should continue their efforts to grow and develop the MSIP program, while maintaining a balanced portfolio of investments by NSF/AST.

Section 4.1.3

Recommendation: The AAAC concurs with *NWNH-AMA* recommendations 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 new facilities and large projects that represent such important and substantial investments by the agencies.

Finding: NSF/AST has successfully demonstrated that it is often possible to secure partners who are capable of extending the productive scientific lifetime of NSF-developed facilities (e.g. the KPNO 2.1m and 4m telescopes) to produce excellent science while reducing the cost to NSF of operating these facilities.

Recommendation: The AAAC supports the NSF approach of working to divest from their funding portfolio aging NSF-developed facilities to partners or non-federal organizations that are able to extend the productive scientific lifetime of these facilities. This approach enables NSF/AST to redirect saved funding to the operations costs of new facilities and maintain a robust grant program.

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 of 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: Efforts by AURA, NOAO, Gemini, LSST, and the proposed new NCOA to implement the recommendations of the *OIR System Report* should be supported by NSF as long as they can be accommodated while maintaining a balanced investment across the portfolio of NSF/AST.

Section 4.3

Finding: The agencies have efficiently and effectively executed the priorities of the decadal survey, given the budgetary constraints under which they are currently operating. In general their prioritization of support for projects and missions closely matches the intent of *NWNH.* The proposed termination of WFIRST, the top-ranked space-based priority from *NWNH*, in FY 2019 would be a striking exception to the way that the federal government has followed the priorities recommended by the community through the decadal survey process.

Section 5

Finding: The CMB-S4 Concept Definition Task-force (CDT) carried out a tremendous effort to present the science and technical requirements for CMB-S4, along with a well-thought-out concept for the CMB-S4 survey, pulling together work from the entire CMB-S4 community.

Recommendation: The AAAC commends to DOE and NSF the report of the CMB-S4 CDT, which we find clearly communicates the results of the CDT's efforts to respond to the charge they were given. We are confident that it will meet the needs of the agencies to inform funding and programmatic decisions in the near term regarding CMB-S4.

Section 6.1

Finding: Strategies recommended in *NWNH-AMA* such as independent cost estimates for projects, international funding partnerships to extend scientific reach, and community outreach about the decadal survey are valuable.

Recommendation: The AAAC recommends that the next Decadal Survey process incorporate strategies that were recommended in *NWNH-AMA* to achieve project cost control, extension of scientific reach through partnerships, and community buy-in to the process.

Section 6.2

Finding: The AAAC applauds the efforts of the NSF, AUI, AURA, and the NSF's observatories to work with the community to help prepare for the upcoming Decadal Survey through their support of meetings and studies designed to investigate science cases, science capabilities, and facilities for consideration by the Decadal Survey.

Recommendation: The AAAC supports the NASA Astrophysics Division CubeSat initiative and recommends it continue to execute Announcements of Opportunity to determine the viability of CubeSats as a valuable component of NASA's efforts in astrophysics.

Finding: The AAAC applauds NASA's efforts to support, working with the community and NASA Centers, the development of well-studied and costed mission concepts for consideration by the Decadal Survey.

Section 6.3

Finding: The AAAC finds that the Decadal Survey process, including implementation of the recommendations by the agencies, is important for ensuring that the US remains a global leader in scientific exploration and technology development.

Section 7

Finding: Delays in passing the appropriations for the agencies for a given FY that extend well into that FY, often accompanied by temporary levels of funding provided by a continuing resolution, may create severe challenges and added risks for the efficient management of programs, missions, facilities, and the award of research grants. If the subsequent appropriation levels require significant cuts to missions or facilities, absorbing the reduction during the remainder of the FY is likely to be extremely difficult, leading to either inefficient application or waste of resources.

Recommendation: The AAAC urges Congress to increase the proposed FY 2019 appropriation for NASA above the President's request, enabling NASA and the administration to maintain their past support for the highest priority of *NWNH* for a new space initiative (NASA's Wide-Field Infrared Survey Telescope, WFIRST), allow a balanced program within NASA astrophysics, and still enable the President's proposed new initiatives for NASA.

Finding: The AAAC is concerned that the proposed FY 2019 budget for DOE High Energy Physics falls at the lower boundary of the scenarios considered by P5. We note that it would be a challenge at this level of appropriations for DOE to continue planning for the existing Major Items of Equipment in development (Dark Energy Spectroscopic Instrument, LSSTCam, SuperCDMS-SNOLAB and LZ) while maintaining an adequate grants program.

Recommendation: NSF and NASA should continue to carry out and evaluate their strategies for reducing proposal pressure, reporting to the community for feedback on their evaluation strategies and the results.

Finding: The statutory deadline, March 15th, for the submission of the AAAC annual report does not allow sufficient time for the committee to react to budget developments that typically occur in the first two months of each calendar year.

Recommendation: The AAAC recommends that the annual report deadline be changed from a fixed date to a deadline 45-60 days following the submission of the President's budget request, so as to enable sufficient opportunity for the committee to interact with the funding agencies, understand the impact of the President's budget, and formulate recommendations. The AAAC would endeavor to still meet the current deadline of March 15th when possible.

1. Introduction

The Astronomy and Astrophysics Advisory Committee[3] (AAAC) was established in the National Science Foundation (NSF) Authorization Act of 2001. Its charge is to monitor and evaluate 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, especially those requiring coordination of the agencies' efforts. The AAAC annually assesses progress in implementation of the recommendations of the most recent decadal survey, *New Worlds, New Horizons in Astronomy and Astrophysics*[4] *(NWNH),* its predecessors, and relevant reports from similarly constituted non-decadal advisory committees. The AAAC reports 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 2017-2018 committee reviewing activities in 2017.

A few notable highlights from the past year, both in research and in engagement with the public, are outlined in Section 2. The cover photo of this report is an artist's illustration of one of the research highlights of 2017, the observation of the merger of two neutron stars: this was first detected through gravitational wave signal emitted during the merger and followed by the observation of an electromagnetic counterpart that was observed by many telescopes at a variety of wavelengths. This ground-breaking observation illustrates the powerful synergies between facilities and marks a new era in multi-messenger astronomy: coordinated observations between multiple signal carriers such as electromagnetic radiation, gravitational waves, and/or neutrinos. It highlights the power for scientific discovery of coordinated effort among science teams, institutions, agencies, and facilities. Further, it provides an early taste of the benefits of coordinated investments in scientific capabilities, which we anticipate will be realized as new facilities like the Large Synoptic Survey Telescope (LSST) come online in the near future. The astronomical community will experience further tangible benefits from synergies between facilities that will maximize the scientific returns from investment in these facilities and programs.

Since March 15, 2017, the AAAC has had two face-to-face meetings and three video conferences. Representatives of the three agencies have given briefings and provided input on the status of their programs. As we finalize this report, the FY 2018 appropriations have not been passed and agencies are on a Continuing Resolution. The Presidents' requested budget for FY 2019 was made public on February 12, 2018, shortly before the last meeting of the AAAC

3 https://www.nsf.gov/mps/ast/aaac.jsp
4 https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

prior to the submission of this report. As we detail further in section 7, our ability to provide the best advice and guidance is constrained by the quality and timeliness of the information we are provided.

This 2017 annual report begins with a summary of selected highlights and 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. We describe the work and accepted report of the CMB-S4 concept definition team, a subcommittee of the AAAC that was active in 2017, followed by an update on preparation by the agencies and the community for the next decadal survey. Finally, we conclude with a summary of the current federal budget situation and its impact on future progress towards fulfillment of the vision in *NWNH*.

2. Highlights of 2017

Every year the AAAC highlights scientific, educational, and outreach accomplishments from the previous year that illustrate the value of the federal investment in astronomy and astrophysics and/or the value of the coordination between DOE, NASA, and the NSF in their investment in Astronomy and Astrophysics. Our selections are not exhaustive or complete, but nonetheless show the effectiveness of the community and agencies working together to realize our common aspirations for the future.

2.1 Outreach highlights

Astronomers and astrophysicists around the country have a long history of engaging with the non-scientific community in deep and meaningful ways. Astronomy is a natural “gateway” science, providing a critical path to STEM interest and education, which has important consequences for building the high-tech workforce of the 21st century. Here we highlight only a small subset of activities carried out over the previous year that have had a major impact on the non-scientific community.

Staff of Arecibo Provide Exemplary Service after Hurricane Maria: In September 2017, Hurricane Maria (one of the most extreme Atlantic Hurricanes on record) caused severe damage and loss of life in the Caribbean. Among the locations heavily impacted by the storm, Puerto Rico, home to NSF's Arecibo Observatory, suffered major damage to essential infrastructure. Despite damage to the observatory, Arecibo staff went far beyond the call-of-duty to assist their community, and made the observatory's resources available to assist in recovery efforts. Examples of contributions from the observatory include the following:

- Providing an average of 14,000 gallons of clean water per day to the community out of the Arecibo Observatory's water well.
- Receiving over 15 flights from FEMA, National Guard and Coast Guard helicopters on the site that provided food and supplies to the local community.
- Coordinating with FEMA for relief personnel to pick up supplies after the airdrop.
- Supporting relief efforts by helping FEMA unload supplies and distribute them among the neighboring communities.
- Cleaning up debris from major roads to restore traffic flow between multiple neighboring communities immediately after the hurricane.
- Providing assistance to the Puerto Rico power authority and local police by allowing them to use Arecibo Observatory repeaters for radio communication.
- Providing mechanical assistance to local government relief entities by repairing damaged water distribution trucks.

Finding: The staff of the Arecibo observatory, which was a federally funded facility during 2017, carried out a variety of critical public services in the aftermath of Hurricane Maria that were of great value to the broader community in Puerto Rico. The AAAC commends and extends our gratitude to the Arecibo staff for their efforts to aid their community and prevent additional loss of life.

The Great American Eclipse of 2017: On 21 August 2017, a total solar eclipse crossed North America from coast to coast for the first time since 1918. In all, the path of totality touched 14 states, coming ashore in Oregon and leaving off the coast of South Carolina. About 215 million Americans watched the eclipse in some way, making this event a factor of two more popular than the Super Bowl that year[5]; about 12 million people live in the path of totality, and millions more travelled to the path, as evidenced by the considerable traffic delays before and after the event. NASA's livestream of the event peaked at 4.4 million people, the most viewed web stream in the agency's history. Major initiatives were mounted to collect both professional and amateur data and images of the eclipse. A partnership citizen science project spearheaded by Google and UC Berkeley collected eclipse images from across the country and are stitching them together into an "eclipse Megamovie" to give a view of the dynamic solar corona for the hour and a half it took the eclipse to cross the country. The Eclipse Ballooning Project[6], led by

[5] https://www.nytimes.com/2017/09/27/science/solar-eclipse-record-numbers.html
[6] http://eclipse.montana.edu

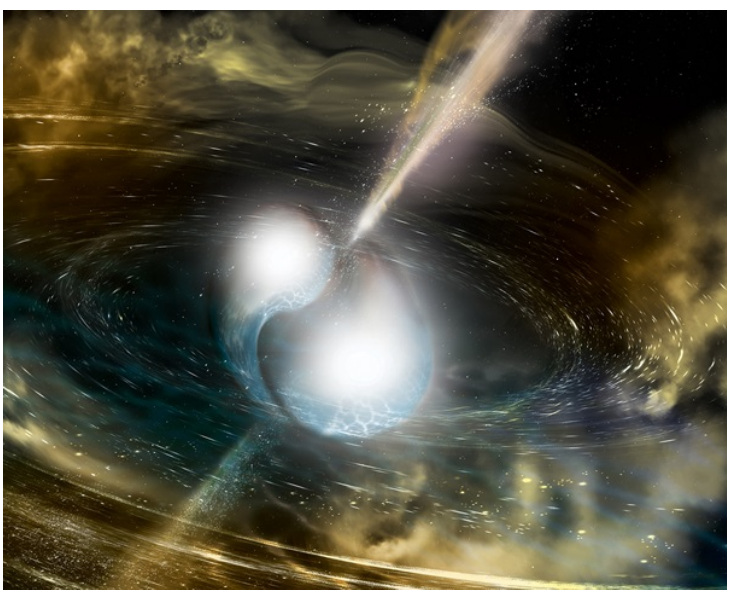
NASA's Montana Space Grant Consortium, coordinated high-altitude ballooning teams from universities across the country to build and fly imaging equipment and sensors on atmospheric sounding balloons in the path of totality. NSF’s National Solar Observatory, together with NASA and commercial sponsors, enabled the Citizen CATE (Continental-America Telescopic Eclipse) Experiment, which distributed more than 60 identical telescopes along the path of totality, operated by citizen scientists and high school and college students, to collect images of the solar corona during the eclipse. CATE produced a unique data set from 68 sites, of which 61 were able to contribute useable data for inclusion in a record of 83 minutes of the possible 93 minutes of totality. The media attention focused on these activities and the eclipse in general was outstanding. Many results are still being released as the large quantities of images and data collected by professionals and amateurs are reduced, collated, and organized.

Finding: The outreach and educational efforts of the astronomical community related to the Great American Eclipse of 2017, as supported by many including the NSF and NASA, were highly successful in developing scientific engagement among the public.

Image credit: NASA/Aubrey Gemignani

2.2 Research highlights

Multi-messenger Gravitational Wave Detection of a Binary Neutron Star Merger:[7] On August 17, 2017, LIGO detected its first ever binary neutron star merger, GW170817. Coincident with the LIGO signal (1.7 sec later), the Fermi Gamma-Ray Space Telescope detected a short gamma ray burst, GRB170817A. The coincidence of signals launched one of the most widespread follow-up observing campaigns in history. Within the first day, using localizations provided by the LIGO-Virgo detector network, six ground-based observatories around the world had successfully detected the counterpart to these signals in the galaxy NGC 4993, 130 million light years away. More than 70 ground-based and space-based telescopes have followed up on the source, watching its evolution for many months afterward. The coincident detection confirms the neutron-star merger model for short gamma-ray bursts, and provided new insights and constraints into GRB jets, kilonova explosions, and the enrichment of the cosmos with heavy elements. Many papers have been published since the discovery. One of the two discovery papers (published in ApJ Letters[7]) included nearly 4000 authors, one of the largest astronomy papers in history.



Artist's illustration of two merging neutron stars. Image credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet

[7] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Phys. Rev. Lett. 119, 161101 (2017), B. P. Abbott et al., *Multi-messenger Observations of a Binary Neutron Star Merger,* ApJ Letters 848, L12 (2017)

Oumuamua 1I/2017 U1: First Extra-solar asteroid[8]

On 19 October 2017 the Pan-STARRS telescope at Haleakalā Observatory, while executing a NASA-funded research program, detected asteroid 1I/2017 U1, colloquially named 'Oumuamua, Hawaiian for `scout'. It is the first known object of interstellar origin to pass through the solar system, and thus bears the first "I" designation from the IAU in its name. It is small and oblong, measuring roughly 35 meters by 230 meters. Its color is similar to asteroid colors in the solar system, and it showed no sign of a cometary tail, suggesting it is high density, metal-rich rock. Given the unusual origin of 'Oumuamua and its outbound trajectory, a widespread observational campaign was mounted to characterize its properties, shape and size, dynamical behavior, and orbital elements. The observing campaign included both ground-based telescopes (Pan-STARRS, CFHT, VLT, Gemini South, Keck, and GBT) and space-based telescopes (NASA's Hubble and Spitzer Space Telescopes).

Artist's illustration of Oumuamua 1I/2017 U1: First Extra-solar asteroid. Image credit: ESO

Most distant known quasar discovered at redshift 7.54 in the early neutral universe:[9]

Using multiple ground-based telescopes (the 6.5m Magellan-1 Baade Telescope at Las Campanas Observatory, the 2x8.4m Large Binocular Telescope at Mt. Graham in Arizona, and the NSF-supported 8.2m Gemini North Telescope in Hawaii), together with data from NASA's NeoWISE satellite, astronomers identified a quasar with a record-breaking redshift of 7.54, consistent with a distance that puts the formation of the quasar's black hole at just 700 million years after the Big Bang. Powered by an 800 million solar mass black hole, the quasar is the

[8] K. J. Mech et al., *A brief visit from a red and extremely elongated interstellar asteroid*, Nature 552, 378-381 (2017); https://doi.org/10.1038%2Fnature25020

[9] E. Banados et al., *An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5,* Nature, 553, 473-476 (2018); http://doi.org/10.1038/nature25180

first known quasar detected in the early cold Universe, before the epoch of reionization when the earliest galaxies reheated the intergalactic gas that had cooled after the Big Bang

This discovery was enabled by partnerships between NSF funded and non-federally funded facilities; the NASA supported NeoWISE, and the DOE and NSF supported the DECam Survey.

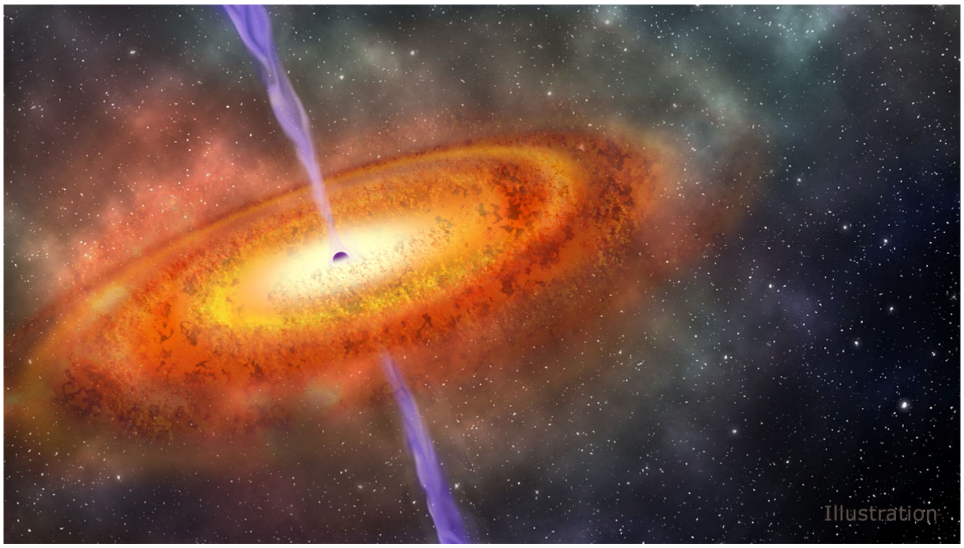


Image credit: Robin Dienel/Carnegie Institution for Science

IceCube- 170922A Ultra-high Energy Neutrino:[10] On September 22, 2017, the NSF-funded IceCube South Pole Neutrino Observatory issued an alert (GCN Circular) for event 170922A, a high energy cosmic neutrino with an energy of ~0.3 PeV, originating within 0.1 degree on the sky from flaring blazar 3FGL_J0509+0541. Follow up observations by Fermi-LAT detected increased gamma ray activity from the blazar, as did observations by the MAGIC imaging Cherenkov Telescopes on La Palma. This is the first strong correlation of a high energy neutrino event with an extra-galactic source.

NASA's Kepler Mission Releases its Final Catalog of Exoplanets:[11] NASA's Kepler mission released its final catalog of 4,034 candidate transiting exoplanets in June of 2017. This catalog includes 2,341 confirmed exoplanets, of which 30 are potentially habitable planets – i.e. those less than twice Earth's size located in the habitable zone around their host stars where liquid

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[10] https://gcn.gsfc.nasa.gov/gcn/gcn3/21916.gcn3

[11] Press release: https://www.nasa.gov/press-release/nasa-releases-kepler-survey-catalog-with-hundreds-of-new-planet-candidates
Publication: B. J. Fulton et al., *The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets*, Astronomical Journal, 154, 109 (2017); http://iopscience.iop.org/article/10.3847/1538-3881/aa80eb/meta

water could exist on the planet's surface. Among the key discoveries of the Kepler mission are that small planets (1-4 times the Earth's size) occur commonly in orbits around the stars in our galaxy and that these planets appear to be further sub-divided into two primary size categories. The larger objects (1.75-4 times the Earth's size) are likely to be gas-rich planets, similar in composition to the giant planets in our Solar System, whereas the smaller objects (less than 1.75 times the Earth's size) are likely to be rocky planets like the Earth, Mars, and Venus.

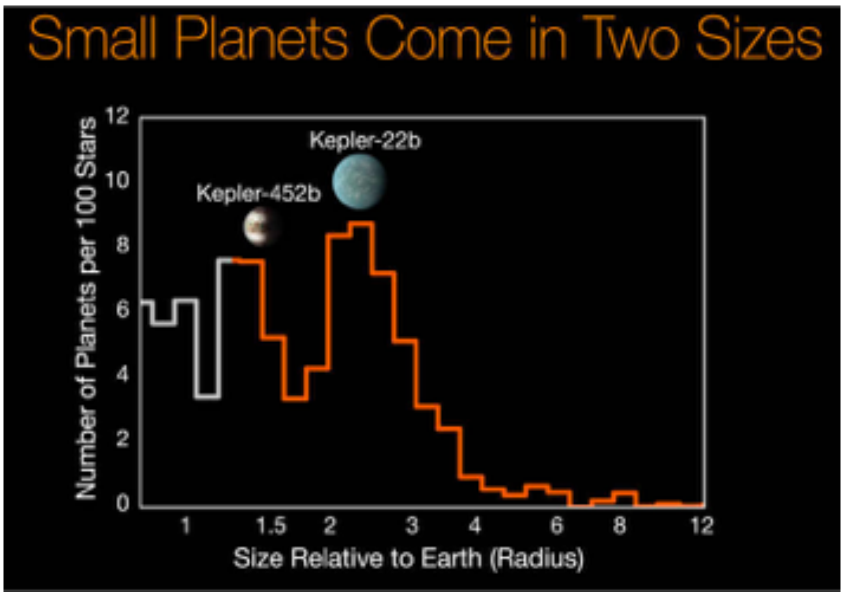


Image credit: NASA/Ames Research Center/CalTech/University of Hawaii/B.J. Fulton

"Grand Finale" for NASA's Cassini Mission:[12] NASA's Cassini mission ended successfully on September 15, 2017, as the spacecraft plunged itself into the depths of Saturn's atmosphere using its remaining rocket propellant and causing it to eventually burn up. Cassini spent over 13 years in orbit around Saturn exploring the planet itself along with its rings and moons. The demise of Cassini was planned so as to leave the potential life-bearing moons of Saturn (e.g. Enceladus and Titan) free of contamination from any accidental future collisions with the

[12] https://saturn.jpl.nasa.gov/mission/grand-finale/overview/

spacecraft. Cassini provided the most in-depth picture of the Saturnian system to date. Highlights of the mission include the discoveries of a global ocean with indications of hydrothermal activity within Enceladus, and liquid methane seas on Titan from the Huygens lander. In its grand finale, Cassini executed a set of orbital maneuvers that carried the spacecraft through Saturn's rings, on a close pass to Titan, skimming through Saturn's upper atmosphere, and ultimately into Saturn itself.

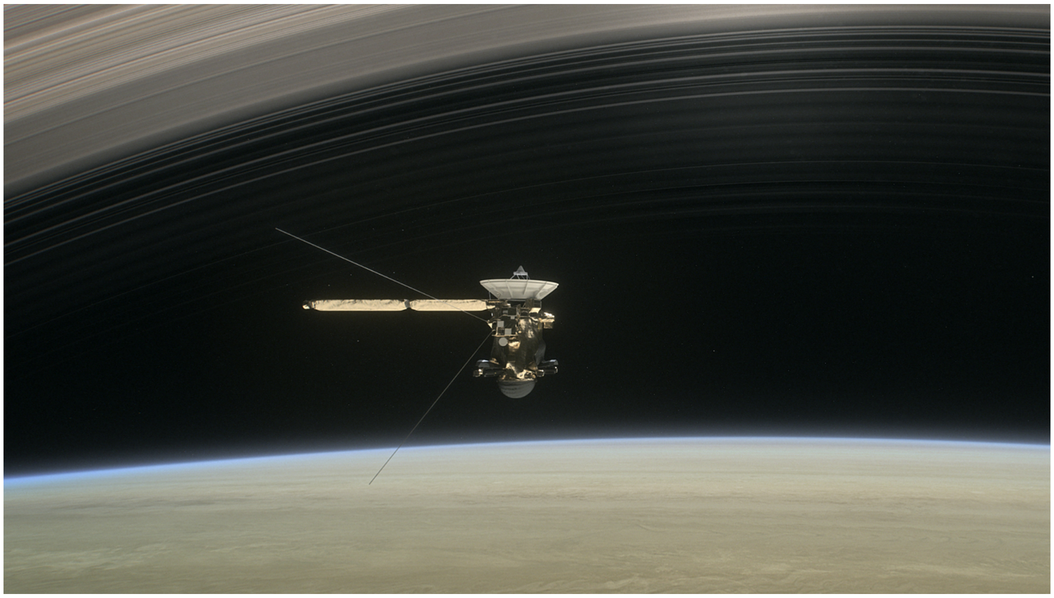
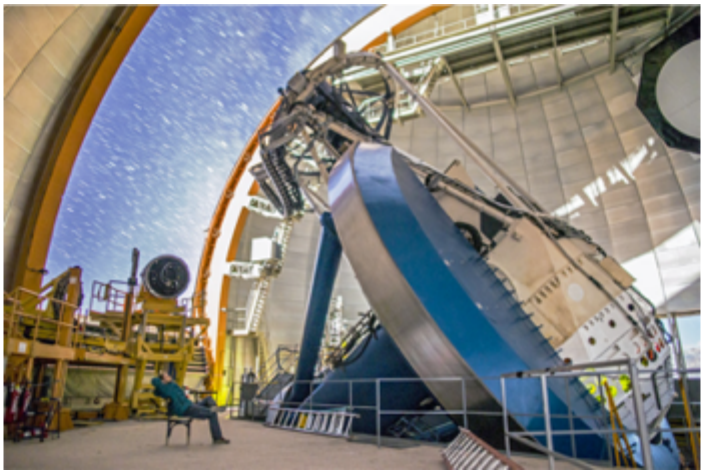


Image credit: NASA / JPL-Caltech

Dark Energy Survey First Data Release:[13] The Dark Energy Survey (DES), funded jointly by the DOE, NSF, and international partners, had its first public data release in 2017. The survey is mapping the properties of thousands of supernovae and hundreds of millions of galaxies to understand the expansion of our universe over cosmic time. The cause behind the accelerating expansion rate of our universe remains one of the fundamental mysteries of modern astrophysics. DES will measure the cosmic expansion rate and map the formation of structure in our universe. The DES first data release (DR1) consists of over 38,000 single exposure images, including observations of nearly 310 million galaxies and 80 million stars. This constitutes the largest dataset of its type to date. One result from DR1 has been the discovery of close to a dozen new stellar streams around the Milky Way, which are the remains of star clusters and dwarf galaxies that have been torn apart by the gravitational force of our galaxy. These stellar streams provide important clues about the formation history and structure of the Milky Way.

[13] Press release: https://www.darkenergysurvey.org/news/dark-energy-survey-publicly-releases-first-three-years-data/



“DECam operating at night, while an observer watches”[14]

eBOSS Measures Baryon Acoustic Oscillations:[15] The Sloan Digital Sky Survey-IV’s Extended Baryon Oscillation Spectroscopic Survey (eBOSS)[16] has released an unprecedented map of the positions of more than 147,000 quasars. Quasars are the incredibly luminous centers of distant galaxies powered by supermassive black holes. The quasar map has been used to detect baryon acoustic oscillations, which are the present day signature of sound waves that traveled through the early universe and are now imprinted on the large scale distribution of galaxies. The BAO observations enabled by eBOSS confirm the standard model of cosmology by directly probing the conditions in the early universe. This new result provides an independent piece of evidence that further supports a model of the universe that is dominated by dark matter and dark energy, whose sources remain unknown.

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 and outreach efforts. Coordination between the agencies was particularly important and valuable in enabling these discoveries.

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[14] Image credit: https://www.darkenergysurvey.org/the-des-project/instrument/

[15] Press release: http://www.sdss.org/press-releases/astronomers-make-the-largest-map-of-the-universe-yet/

[16] The Sloan Digital Sky Survey-IV’s eBOSS is funded by the DOE, the Sloan Foundation and SDSS-IV member institutions.

3. Overview of Interagency Coordination and Cooperation

3.1 Past and Current Coordination and Cooperation

Astronomy and astrophysics have historically been areas of strong interagency coordination and cooperation. For example, rapid gravitational-wave detection by the LIGO-Virgo team, coupled with Fermi's gamma-ray detection, enabled follow-up by telescopes around the world, including those supported by all of the US agencies. Ongoing surveys, the extended Baryon Oscillation Spectroscopic Survey (eBOSS) and the Dark Energy Survey (DES), are currently collecting data and have released their first scientific results, while construction is proceeding on their successors, the Dark Energy Spectroscopic Instrument (DESI) and the Large Synoptic Survey Telescope (LSST). 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. Studies of the cosmic microwave background routinely involve contributions from the three agencies, e.g. DOE involvement in the South Pole Telescope managed by NSF or providing computing for NASA's involvement in the Planck Satellite. The principal instrument for the Fermi Gamma-ray Space Telescope was built in partnership with DOE and has support from DOE during the operations of Fermi. The science mission of Fermi was enhanced and supported by ground-based follow-up and supporting observations made by NSF and NASA supported facilities. NEID, a NASA-funded instrument with time provided by NSF/NOAO on the WIYN 3.5m, a facility supported by NSF and U.S. Universities, will supply necessary ground-based support to a NASA space-based mission (TESS). These, and other major survey projects, would not have been possible without the coordinated collaborative efforts of multiple agencies. The agencies also collaborate on decadal survey sponsorship, coordinated ground-space observations, detection of Near Earth Objects, the exoplanet research program and many others.

Finding: NSF, DOE, and NASA continue to work 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.

3.2 Opportunities for Future Coordination and Collaboration

In addition to the recognized past collaborative efforts mentioned above and those in progress or proposed in section 4, we highlight here opportunities for collaboration that are consistent with the on-going efforts of all the agencies, but which deserve being highlighted here because they do not map perfectly into our discussions in section 4. These include efforts to broaden the impact of important data sets, supporting coordinated analysis of the results of major independent surveys, communicating and coordinating the impact of each agency's portfolio (or similar project) reviews, and protecting the accessibility of the electromagnetic spectrum for astronomical observations.

Public Release and Curation of Data and Results from major Simulations and Surveys: Much of the success of the latest generation of astrophysical studies (including the results of massive simulations) and cosmology surveys has been enabled by the scientists conducting the research generating thoughtfully conceived data sets, databases, data access tools, and software for analysis and simulation of data sets in addition to producing the original scientific data. The benefits and scientific productivity gains from investment in the tools to provide access to a broad community to the data and data products have consistently and significantly outweighed the cost to provide such tools. As astronomical datasets grow both in size and complexity and the expectations for scientific reproducibility grow, it will become ever more important to release the relevant software along with the data. There is an ongoing NAS survey on open software policies for NASA.[17] These data releases, with or without associated software releases, impose significant costs and raise issues of long term management and curation.

Finding: Astronomical surveys and major astrophysical simulations (for example, but not limited to, cosmological simulations) have broader and greater impact if in addition to the generation of high quality data sets and clear presentation of their results, the data and derived data products are made public along with appropriate tools to access the data products. When the software used to generate the data and data products is also publicly available, it is more straightforward for other researchers to produce new scientific results with the dataset, as well as to reproduce and verify previously-reported scientific results.

Finding: Public data releases, including data access tools, software used to generate the data and data products, and documentation of the data, software, and access tools, are quite costly and deserve curation in order to realize the potential of increased long-term impact of such availability of the data sets and related materials.

[17] http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_178892

There are existing standards on virtual observatories[18] (VOs) that are implemented in all NASA data archives. However, data releases throughout the field of astronomy more generally do not follow consistent patterns in terms of how the data can be accessed, what type of data is released, documentation, release of software tools, and other practical details that impact how the publicly released data can be used in practice.

Recommendation: All current and planned surveys should publicly release their data with suitable access tools and documentation. This is consistent with the AAAC Principles of Access recommended by the AAAC in their 2013-2014 annual report. In addition, the surveys should release the source code used to create the data products. Surveys supported in part or entirely by the federal government through its agencies should work to include funding enabling adequate public access to the data, software, and data products produced through these surveys.

Recommendation: The three agencies should coordinate, and where possible standardize, the guidelines and expectations for the releases of data sets, data products, data access tools, and related software used to produce future surveys, astrophysical simulations, and missions. The goal of this coordination should be to help researchers efficiently provide access to the data they produce through tools useful for the broad scientific community with minimal duplication of effort between agencies and stakeholder groups. Release and documentation of the software used to generate and analyze the data will enhance the quality of current and future science by enabling more cost effective reproducibility and extension of the scientific results from the initial studies.

Coordinated analysis and other synergies between LSST, Euclid, and WFIRST: LSST, Euclid, and WFIRST, while distinct and separately funded and managed projects as described in Section 4, enable surveys with strongly overlapping science goals, particularly in the study of dark energy. The data sets that each will produce, while targeting overlapping science, are unique and complementary. For some science goals, each mission is self-contained in being able to meet their scientific requirement with their own data, but it has been recognized for several years that the potential synergistic relationship between these missions might enable important and additional science opportunities beyond those proposed for each mission. Further, the data to be generated by LSST might be particularly valuable to ensuring the realization of the proposed science from Euclid and WFIRST. The recognition of this potential synergy led to the establishment of a "Tri-Agency Group" (TAG; an agency-only group) and a "Tri-Project Group" (used to refer to the inclusion of project leaders). These groups have been holding informal telecons every two months with yearly face-to-face meetings focused on the potential for how analysis of the combined data sets might further the study of dark energy. An additional group, focused on computing that crosses projects, has also been created. The

[18] http://www.ivoa.net/deployers/intro_to_vo_concepts.html

AAAC noted in our last report that we believe it would be beneficial to a broader range of high priority science areas (as represented in the decadal surveys) if other stakeholders were brought into these discussions.

In addition to the above, there are other ongoing attempts at coordination between Euclid and LSST. Informal discussions within and between the Euclid and the LSST Project team have occurred on whether currently out-of-scope (for LSST), low-level joint data processing could be beneficial to some science areas. There could be many additional synergies between the projects in theoretical and data analysis investigations, cadence, and area overlap, though this has only just begun to be explored. The most recent publicly-available document describing these synergies[19] focuses primarily on cosmological science but does have preliminary investigations into other scientific areas.

The AAAC recognizes that if coordination can be realized, it is likely to increase the scientific productivity of Euclid and LSST. However, currently appropriated funding from NSF and DOE for LSST is to complete the construction of the observatory and to prepare for the start of the surveys that led to the LSST's high rank in *NWNH*. The AAAC recognizes that while planning for operations is part of the construction budget, planning for coordinated data analyses with Euclid during operations and executing such a revised plan would be out of the current scope and if supported should be through an augmentation to the construction and operations budgets for LSST.

Finding: **The tri-agency and tri-project groups have conducted useful investigations to explore coordination between science teams planning to use LSST and Euclid to further the study of dark energy.**

Recommendation: We recommend that the three agencies either broaden the current discussions or create parallel discussions to consider broadly the costs and benefits of coordination on the science areas of interest to both the Euclid and LSST communities. We recognize that if a decision is made to plan for coordination between LSST and Euclid during construction of LSST and to execute such a plan during LSST operations, the budgets for both the construction and operation of LSST would likely need an augmentation.

Coordinated agency portfolio reviews: The DOE is conducting a portfolio review that will evaluate the scientific impact and productivity of several experiments that are coordinated with the NSF. We note that the DOE portfolio review process as presented will keep partner agencies and institutions apprised of the HEP portfolio review plans as well as resulting decisions. The NSF expects to conduct a portfolio review in response to the Decadal Survey and the projection that facilities support will become two thirds of the NSF AST budget in the

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[19] Rhodes et al. (2017), *Scientific Synergy between LSST and Euclid*, Astrophys. J. Supp., 233, 21; http://adsabs.harvard.edu/abs/2017ApJS..233...21R

near future. NASA regularly performs a similar evaluation of its mission portfolio in its Senior Reviews, which are required by law. Many of the experiments, projects, missions and facilities that are or will be under review are joint efforts coordinated with one or more agencies.

Finding: **The AAAC appreciates that the agencies are attempting to preserve a balanced portfolio in the face of significant budget pressure and realize the goal of keeping projects currently under construction on schedule and on budget.**

Recommendation: **The agencies should continue to prioritize a balanced portfolio, and in particular maintain a viable research and analysis program, using existing mechanisms familiar to the community such as the portfolio reviews and pacing of the early funding and review milestones for new projects. The agencies should communicate clearly with the community as these processes evolve to match the pressures on their programs.**

Finding: The portfolio reviews and other processes for the assessment of current missions, projects, and facilities, are important tools for the agencies to maintain a balanced portfolio between new projects, operation funding for current facilities, missions and experiments, and research funding for science analysis and technology research and development. The AAAC is supportive of the agencies using the portfolio reviews to help maintain a balanced program.

Recommendation: **The agencies should continue to communicate with each other about current and future portfolio reviews and consider how joint projects between agencies are meeting the priorities of all stakeholders.**

The Era of Multi-messenger Astronomy: As described in sections 1, 2 and 3.1, it is now clear that the emerging field of multi-messenger astronomy - while not well-anticipated by *NWNH* - has tremendous potential that can be realized with support from researchers and facilities enabled by all three agencies.

The gravitational wave observation by NSF's LIGO of coalescing neutron stars followed by prompt detection of the source in multiple electromagnetic wavelength bands had significant contributions from both ground-based telescopes and space missions. For example, the Fermi Gamma-ray observatory detected gamma rays from the merger nearly coincident in time with the LIGO detection (2 second delay). In conjunction with ground-based observations of the afterglow associated with GW170817, this led to a better characterization of so-called kilonova emission and strong support for theories identifying such merger environments as a site for the synthesis of elements.

NSF's IceCube South Pole Neutrino Observatory detected a high energy cosmic neutrino with an energy of ~0.3 PeV, originating within 0.1 degree on the sky from the blazar 3FGL_J0509+0541 on September 22, 2017.   Follow-up observations by NASA's Fermi-LAT detected increased gamma ray activity from the blazar, as did observations by the MAGIC imaging Cherenkov Telescopes on La Palma. This is the first strong correlation of a high energy neutrino event with an extra-galactic source.

The events observed by LIGO and IceCube that were also observable with sensors detecting associated electromagnetic radiation herald the start of multi-messenger astronomy.
In 2016, the NSF introduced a set of Big Ideas,[20]aimed at long-term development of visionary frontier directions in science and engineering. The era of multi-messenger astronomy is emphasized in one of these: "Windows on the Universe". New syntheses of observational approaches are needed to provide deeper insights into the nature and behavior of matter and energy and help to answer some of the most profound questions. Since its beginnings, astronomers have made observations in the optical regime of the electromagnetic spectrum. Since the middle of the twentieth century, our grasp has steadily expanded to include observational capabilities ranging from radio waves to X-ray and gamma rays, up to amazingly high energies accessible with air shower experiments on the ground. Today we speak of multi-wavelength astronomy. Many great discoveries have been made as a result of rapid technology developments across the spectrum. Presently we are able to observe the world around us in fundamentally new ways, as we expanded into the realm of neutrinos and gravitational waves. While not limited to these new frontiers, the utilization of the full portfolio of instruments and observatories will advance our knowledge to unprecedented levels.

Finding: **The AAAC applauds the NSF and NASA for having supported the first steps into the exciting new field of multi-messenger astronomy. These initial results for multi-messenger astronomy are impressive achievements and are important examples of science benefiting from interagency coordination, combining LIGO, the Fermi satellite, IceCube, and many other space and ground-based facilities observing across the electromagnetic spectrum. Multi-messenger astronomy is clearly a well-stated priority of the NSF and is explicitly (NASA's support of space missions enabling this science as part of their science mission) and implicitly (DOE's partnership with NSF in projects and facilities that support the NSF's goals for this science) enabled by the other agencies.**

Finding: The AAAC recognizes that NASA's space mission portfolio has great potential for supporting the emergent area of multi-messenger astronomy that has been opened by the NSF supported observations of gravitational waves and high energy particles, including neutrinos. The AAAC further recognizes that existing agency partnerships (e.g. between DOE and NSF for LSST) have the potential of further supporting the development of multi-messenger astronomy and astrophysics.

Recommendation: The AAAC supports an intensification by NSF and NASA of existing collaborations that support multi-messenger astronomy, inspiring a new generation of

[20] https://www.nsf.gov/news/special_reports/big_ideas/

engineers and scientists to work in this emerging area.

Recommendation: **The AAAC recommends that all three agencies, in recognition of the compelling science opportunities provided by the emerging field of multi-messenger astronomy, do their best to support the capabilities, facilities, missions, and programs on which progress in this area depends. For the NSF, multi-messenger astronomy is a well-recognized high priority.[20] We recommend that DOE and NASA stay in close communication with NSF to avoid inadvertently hindering, through actions affecting their own programs or missions, this high priority of their partner agency.**

Protecting the electromagnetic spectrum for astronomical research: The electromagnetic spectrum is a limited resource subject to unrelenting and competing pressure from commercial, military, and scientific uses. The rapidly growing prevalence of moving emitters, including cell phones, car radars, and satellites, compounds the problem of protecting astronomical observatories from contaminating emission. Frequency bands "protected" for astronomical use were primarily defined before the early 1970's, based on a few key emission lines known at that time.

The impact of optical light pollution has been known and characterized for decades, which has resulted in municipalities electing to pass "light ordinances" or codes to limit the impact on observations with nearby telescope facilities. However, new issues continue to threaten astronomical observations. For example, the recent transition to LED lights has created a haze of light in the sky due to their strong blue color, which is highly scattered by the atmosphere. While optical light pollution had been increasing at roughly 6% per year before the transition to LED lights, the annual increase is now approaching 15%.

Less well-known is the impact of light pollution outside the visible spectrum, primarily because the results are "invisible" to the human eye. Access to particular wavelengths of light is regulated by the FCC (for non-government entities domestically), NTIA (government organizations), and the International Telecommunications Union (internationally). The process through which wavelengths are protected or allocated is highly complex, and dependent on a range of political and commercial interests. Although both the NSF and NASA have staff assigned to spectrum management, and the National Academies sponsors the "Committee on Radio Frequencies" (CORF), the limited resources and personnel available strongly limit the influence of astronomical requirements on wavelength allocation.

Subsequently, the original protected frequency regions have been eroded both from external challenges, as well as significant out-of-band emission from competing sources and harmonics overlapping with key astronomical lines. The original protected frequencies do not include emission lines that have become increasingly important as astrophysical diagnostics since the 1970's, nor do the protected frequencies encompass known lines that are redshifted out of the protected bands.

Variable (moving) contaminating sources also threaten the ability of astronomers to carry out multi-messenger observations that enable new discoveries. Particular challenges in the upcoming decade will include satellite services (especially broadband internet providers from constellations of satellites), high altitude platform systems, and other emissions from moving sources (such as radars in automobiles, or drones). This risk is particularly heightened for time-domain science, for which the necessary frequencies must be available within a limited window of time.

Although ground-based observatories, and in particular radio observatories, are traditionally thought of as the main casualties of electromagnetic interference, it is important to note that all astronomy relies on protected allocations in the electromagnetic spectrum. Electromagnetic radiation is also essential for conducting space missions. In particular, NASA relies on specific radio frequencies to communicate with missions and return scientific data. For example, the Hubble Space Telescope, the Chandra X-Ray Observatory, and the upcoming JWST all rely on protected allocations to communicate with NASA. Communication over radio frequencies is also the means by which onboard problems can be diagnosed and mitigated. The Deep Space Network (DSN) utilizes large radio antennas around the globe to maintain communication as the Earth rotates, and disruption in this communication could be disastrous.

Finding: Competing interests continue to provide a severe and unrelenting threat to astronomers' ability to detect emission originating outside of the terrestrial sphere. Without clean access to these wavelengths, the ability of astronomers to obtain fundamental knowledge about the universe is profoundly impaired.

Finding: The resources currently available to the NSF and NASA are not sufficient to protect essential astronomical wavelengths in an arena of competing commercial interests with deep financial support and professional lobbyists.

Recommendation: NASA and NSF should enhance their collaboration with each other and with other groups, including international agencies and commercial interests, to protect the accessibility of essential astronomical wavelengths to researchers.

Recommendation: Efforts, ideally coordinated with all three agencies, should be made to increase awareness of spectrum management issues among astronomers, the general public, and government agencies. Possible agents for meeting this recommendation might include the NSF-funded national facilities for operations at radio and optical wavelengths.

4. Implementation of Decadal Survey Recommendations

4.1 Priorities Addressed or Under Implementation

Ongoing programs, facilities, or missions that were highlights of past decadal surveys are included in this section 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 significantly begun or not yet supported by the agencies, are discussed in section 4.2.

4.1.1 Space-based Projects

The *Wide-Field Infrared Survey Telescope* (*WFIRST*): WFIRST was the top space-based recommendation of *NWNH*, and is designed to address the *NWNH* themes of dark energy, exoplanets, and galaxy evolution science. In 2012, NASA received a telescope originally intended for another purpose by another government agency.[21] The availability of this telescope, with its larger primary aperture than proposed in *NWNH,* led to a reimagining of the recommended WFIRST. Concern regarding the cost and schedule of WFIRST led the mid-decadal review (*NWNH-AMA*[22]) to recommend an independent review of the project. In 2017, the WFIRST Independent External Technical/Management/Cost Review *(WIETR)* was commissioned by NASA and their report was issued the same year.[23] The *WIETR* reaffirmed the importance of the science goals of the mission and the team's ability to develop and execute the mission. The *WIETR* report included recommended steps to bring the mission cost back down to a cost of $3.2 billion. The *WIETR* identified options for reducing cost that included making the coronagraph instrument a technology demonstrator, making small changes to the wide field instrument, and identifying contributions to be made from international partners. Even if the coronagraph were pursued only as a technology demonstrator, a significant science capability would be delivered to the community. Further independent cost assessments were recommended to be made by March 2018, with the review needed to proceed to Phase B following shortly thereafter. In his memo of October 2017,[24] NASA Associate Administrator for the Science Mission Directorate, Dr. Thomas Zurbuchen, outlined the near term plan of assessment and decision points for WFIRST, consistent with the recommendations in *WIETR*,

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21 NASA has never identified the NRO as the source of the telescope, but at the time the availability of a 2.4m telescope was made public, it was widely reported (e.g. http://content.time.com/time/health/article/0,8599,2116436,00.html?iid=tsmodule) that the NRO was the source.

22 http://sites.nationalacademies.org/ssb/CurrentProjects/SSB_161177

23 https://www.nasa.gov/feature/nasa-receives-findings-from-wfirst-independent-review-team

24 https://www.nasa.gov/sites/default/files/atoms/files/final-wietr_memo-signed-171019.pdf

that would continue to support the realization of a mission that would realize the science goals for WFIRST proposed in *NWNH.*

Finding: NASA's Wide-Field Infrared Survey Telescope (WFIRST), following either path described in the NASA Associate Administrator Dr. Thomas Zurbuchen's memo of October 2017,[24] would deliver the science identified for the version of WFIRST recommended in *NWNH:* dark energy, exoplanets, and galaxy evolution.

Finding: A NASA Wide-Field Infrared Survey Telescope (WFIRST) that retains the 2.4m telescope, a wide-field instrument, and a coronagraph would deliver the science identified for the version of WFIRST recommended in *NWNH* and provide a technology demonstrator for future coronagraphic imaging missions.

Recommendation: The AAAC supports the recommendations of the 2017 WFIRST Independent External Technical/Management/Cost Review (*WIETR)* report and the subsequent process implemented by the NASA Associate Administrator in October of 2017 for realizing the science that would be delivered through the *Wide-Field Infrared Survey Telescope*. The AAAC agrees with the need to maintain cost containment for the WFIRST mission, and supports a rigorous cost assessment and mission review prior to WFIRST entering Phase B.

The President's requested budget for FY 2019 does not include funding for WFIRST.[25] The decision to eliminate funding for WFIRST was made in the context of a choice by the administration to reduce the funding for the NASA astrophysics division in support of funding other priorities and the inability of the remaining funds to support a balanced portfolio of investments if funding for WFIRST were retained within the aforementioned reduced astrophysics budget.[26] The imminent launch of JWST was also cited as mitigating the negative impact on astrophysical research of the removal of WFIRST from NASA's plans for the future. However, it is important to note that JWST, while a powerful instrument, does not replace the wide-field capabilities of WFIRST, but rather will have complementary capabilities and scientific impact.

As noted in previous annual reports, the AAAC supports balanced investments by all the agencies as a method of ensuring maximal scientific impact over time. We also continue to strongly support the federal government respecting the integrity and importance of the decadal survey process for identifying the priorities for the agencies engaged in supporting astronomical and astrophysical research. Ending the funding of WFIRST is in conflict with the successful past practice of the agencies trying to realize, in partnership with the community, the aspirations of the decadal surveys. Moreover, it jeopardizes US leadership in space-based OIR astronomy.

[25] https://www.nasa.gov/sites/default/files/atoms/files/fy19_nasa_budget_estimates.pdf
[26] https://www.whitehouse.gov/wp-content/uploads/2018/02/msar-fy2019.pdf

Finding: The President's requested level of FY 2019 funding for NASA's Astrophysics division is not large enough to enable both a balanced portfolio of investments in Astrophysics and the funding for NASA's Wide-Field Infrared Survey Telescope (WFIRST).

Finding: The proposed termination of WFIRST, as presented in the President's requested FY 2019 budget for the astrophysics division of NASA, would result in the withdrawal of federal support for the highest ranked priority for space from *NWNH.*

Finding: A balanced investment by NASA in astrophysical research, including a mix of major, medium, small, and individual research awards, is recognized by the AAAC as the preferred path for NASA to maximize its impact in astrophysical research.

Finding: The AAAC strongly supports the federal government respecting the integrity and importance of the decadal survey process for identifying the priorities for the agencies engaged in supporting astronomical and astrophysical research.

Recommendation: In order to maintain a balanced investment in astrophysical research while continuing to support WFIRST, the highest ranked priority for NASA by the most recent decadal survey, *NWNH,* we recommend that the NASA budget be increased above the Presidents' request to allow a funding level for the astrophysics division that would enable the funding of WFIRST to continue in the context of a balanced portfolio of investment.

The Laser Interferometer Space Antenna (LISA): LISA is a low-frequency gravitational wave observatory that will observe at gravitational wave frequencies in the millihertz regime. It will be ideal for studying ultracompact binary systems in the galaxy, supermassive black hole mergers within the cosmological horizon, and testing general relativity in strongly gravitating systems. The European Space Agency (ESA) has adopted LISA to address its science theme of "The Gravitational Universe," with NASA participating as an international partner. 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*. A LISA Study Office has been created at NASA GSFC and a U.S. LISA Study Team (LST) has been established, with broad spectrum of members from across the US astronomical community. A new LISA Preparatory Science (LPS) program Announcement of Opportunity appeared in early 2018 as an element of the 2018 ROSES call.

Finding: The AAAC supports the continued development of the US participation in LISA, following the guidance outlined in *NWNH-AMA.*

Euclid: Euclid is an 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, or EC (this includes 10 people at DOE labs). US participation in the EC now stands at about 80 PhD scientists. 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) 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*.

Explorers Program Augmentation: [27] This NASA program of comparatively 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* for NASA is significant expansion of the NASA Explorer program, including at least four Explorer Announcements of Opportunity (AO) during this decade, each call including a Mission of Opportunity (MO) call and mission selection. *NWNH-AMA* reiterated that NASA should preserve this goal to provide opportunities for the rapid realization of new scientific opportunities in space. NASA accepted this goal and is on track to realize the planned number of missions. Selected or in progress missions include TESS (a Medium-class Explorer, MIDEX), Imaging X-ray Polarimetry Explorer (IXPE; a Small Explorer, SMEX), NICER (a MO), and GUSTO (a MO). The MIDEX AO in 2016 led to three selected MIDEX proposals (Arcus, FINESSE, & SPHEREx) and three Missions of Opportunity (CASE, COSI-X, and ISS-TAO) that have begun their nine month mission concept studies. A fourth SMEX call is planned for 2019. According to current plans, NASA is on track to achieve the planned four Explorer program announcements of opportunity, each with a Mission of Opportunity and mission selection for the decade.

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 finds that with the planned Announcement of Opportunity for the Explorer program in 2019, the NASA Astrophysics Division is on target to meet *NWNH*

[27] https://explorers.gsfc.nasa.gov/index.html

and *NWNH-AMA* recommendations with respect to the number of Explorer program opportunities this decade.

TESS: The Transiting Exoplanet Survey Satellite (TESS) is a medium-class explorer mission slated for launch in 2018. The mission aims to survey the nearest stars for transiting exoplanets, including potentially habitable worlds. Guest observer programs were announced in early 2018 and the community response was excellent. TESS will operate in conjunction with ground-based facilities to verify candidates and obtain planet masses with high precision radial velocity techniques and will also identify nearby exoplanet targets for follow-up observation by the upcoming JWST mission. In addition to its planet program, TESS will contribute significantly to several scientific topics under the general umbrella theme of Time Domain Astronomy.

Neutron Star Interior Composition Explorer (NICER): In early June of 2017 a Falcon 9 rocket delivered NASA's Neutron Star Interior Composition Explorer (NICER) to the ISS. This mission was successfully extracted from the rocket and installed on, delivering scientific data just a few weeks after launch. Operating in the X-ray regime, one of the mission's emphasis is timing analysis of emission from accreting neutron stars. These observations are of great interest for the effort to reveal the pressure-density relationship of nuclear matter, which in turn is a sensitive probe of the strong force under extreme conditions. The early results from NICER on an X-ray burst from Aql X-1 indicate that data from this mission is opening a new part of discovery space. NICER also enabled a technology breakthrough in the area of "navigation by the stars". The aptly named Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) used signals from pulsing X-ray sources in the Milky Way to establish the position of the ISS with an accuracy of 6 miles. This is an accuracy level competitive with traditional navigation techniques employed for space probes in the outer solar system, where radio signals from Earth are weak. This new mode of navigation thus offers a powerful tool to complement NASA's Deep Space Network of radio telescopes. NICER/SEXTANT is yet another example of the power of synergy and the value of creative use of resources in support of exploration. We now use pulsed radio emission from neutron stars to search for gravitational waves and may soon use X-ray from such objects for navigation of space probes.

GUSTO: The Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO), an Explorer Mission of Opportunity, will fly an Ultra-long Duration Balloon carry a submillimeter telescope capable of observing carbon, oxygen, and nitrogen emission from the interstellar medium. GUSTO will map out large sections of the plane of our Milky Way and provide the first complete study of all phases of the stellar life cycle. The mission is currently scheduled in Phase B and scheduled for launch in December 2021.

IXPE: The Imaging X-ray Polarimetry Explorer (IXPE) uses the state of polarization of light from astrophysical sources to provide new information about the production of X-rays by and around objects such as neutron stars, the winds of pulsars, and black holes. The mission is scheduled for a launch in 2020.

The 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. Projects as complex and large as JWST often require more than a decade to complete. The work to complete JWST has continued throughout 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, enabling unique studies of highly redshifted stars and galaxies of the early Universe. In 2017, the telescope and instruments completed assembly and were moved from NASA Goddard Space Flight Center to Johnson Space Center, where they underwent successful cryogenic testing, some of which occurred as hurricane Harvey struck Texas. The Telescope and instruments are to be mated with the spacecraft and sunshield assembly in 2018. Early release science programs were announced in 2017, and the Cycle 1 call for proposals will take place in spring, 2018. Launch of JWST is currently scheduled to occur in early to mid-2019. The AAAC was briefed in January 2018 by NASA that a launch delay for JWST as late as mid-2019 could be accommodated within the planned budget. As we complete our report, NASA informed us that an independent schedule review is being conducted and the result of that review will be known by April 2018.

Finding: The AAAC commends NASA and the extended team delivering JWST for their encouraging progress toward a 2019 launch of what will be the most powerful telescope ever launched into space.

Finding: The AAAC applauds the extended team working to deliver JWST for their successful efforts to complete the cryogenic tests during Hurricane Harvey in 2017.

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 instrument, as well as the upgraded Germany-provided GREAT Terahertz array, were commissioned in 2016. Development of the next generation US-provided instrument, the High Resolution Mid-Infrared Spectrometer, was initiated in 2016. A next generation SOFIA instrument solicitation was released on March 6, 2018 with a proposal deadline of August 1, 2018.

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 particularly relevant scientifically 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 in the highest priority category 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. In addition to ongoing progress on facility construction (supported by the NSF) and the LSST camera (supported by DOE), 2017 also saw the initiation of joint-agency planning for LSST operations funding, with full survey operations intended to start in FY 2023. NSF/AST stated that the NSF share of the operations funding does represent a significant fraction of the annual expenditures of the Division and a continued flat-funding profile would require a major revision of the planned support for the suite of facility operations in order to preserve a balanced portfolio including support of the grants program.

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

Recommendation: The AAAC urges NSF and DOE to put in place a long-term operations plan and research plan that will, while maintaining a balanced overall portfolio, ensure that the US science community can capitalize on the substantial investment in LSST.

Mid-Scale Innovations Program (MSIP)*:* As another priority for large ground-based programs, *NWNH* recommended the introduction of a competed grants 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.* 40 pre-proposals are being reviewed for the current MSIP program. In addition to the ATI program, which is delayed till next year, NSF/AST stated that funding for the MSIP program will be one of the principal areas impacted by ongoing budget uncertainties along with the individual investigator programs, with both implications for funding levels for successful proposals and success rates.

Finding: The AAAC recognizes and applauds the efforts by NSF/AST to develop and sustain the Mid-Scale Innovations Program (MSIP). The scale and types of programs supportable by MSIP are challenging to realize through any other existing funding program.

Recommendation: NSF/AST should continue their efforts to grow and develop the MSIP program, 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 that is currently under construction. DESI operations will begin in FY 2020. 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, which is operated by AURA/NOAO on behalf of the NSF. Conversion of the top end of the telescope started in February 2018. 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. A review of Project status & Operations plan was conducted in February 2018. In 2017, the DECaLS (DECam Legacy Survey), covering two thirds of the DESI survey footprint, continued. It produced the fifth data release (DR5) in October 2017, 75% complete at that time. DR6 was released in February 2018, but will be described in the AAAC 2018 report. Imaging surveys in support of target selection for DESI of the northern sky, MzLS (using the Mayall 4m in the z-band) and BASS (imaging using the University of Arizona's Bok 2.3m telescope), have respectively been completed and is scheduled to be completed in 2018, respectively.

***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 Haleakalā Observatory in Hawaii, for which the completion of construction is planned for no later than June 2020.

LIGO: The NSF-funded 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* and was recognized with the 2017 Nobel Prize in Physics, awarded to Kip Thorne, Rainer Weiss, and Barry Barish. On August 17, 2017, LIGO observed the gravitational wave signature of two merging neutron stars. Two seconds later the Fermi Gamma-ray Space Telescope saw a coincident short gamma ray pulse. *Science* awarded the 2017 Breakthrough Discovery[28] for the detection and subsequent study of the event, which they stated was "easily the most studied event in the history of astronomy, with 3674 researchers from 953 institutions collaborating on a single paper summarizing the merger and its aftermath." These observations initiated the new window of multi-messenger astronomy, and in the case of the first binary neutron star merger the only missing signature was in the neutrino-sector. Future detections of such mergers may be closer to Earth to allow neutrino detections with NSF's IceCube South Pole Neutrino Observatory.

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 NSF's Blanco 4-meter telescope in Chile, which is operated on behalf of NSF by AURA/NOAO/CTIO. Having just finished its fifth observing season, DES has released cosmological measurements and constraints from the year 1 data and has, in January 2018, made publicly available the first 3 years of survey data.

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

[28] http://vis.sciencemag.org/breakthrough2017/finalists/#cosmic-convergence

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 and reached a key sensitivity threshold (sensitive to the particle physics axion DFSZ dark matter candidate) in August 2017.

Cosmic Microwave Background: Commissioning of the 3rd generation South Pole Telescope (SPT-3G) instrument has been completed and operations started in January 2017. *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 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. The AAAC accepted the CMB-S4 CDT report in October 2017. More information about the CDT is provided in section 5. Following the report, DOE Laboratory groups have set up a pre-Project Design Group in coordination with the CMB-S4 collaboration, for pre-conceptual planning.

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 5 observing began in fall, 2017, and the Cycle 6 deadline is in March 2018. Science highlights include the imaging of an outflow envelope emitted by a low-mass star, U Antliae, late in its life, from which it was shown that the outflow occurred at a high mass-loss rate about 2700 years ago over a limited period of about 100 years. *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.

Karl G. Jansky Very Large Array (JVLA): With traceable roots back to at least the report *Ground-Based Astronomy: A Ten-Year Program*[29] (A. E. Whitford, 1964) and recommended by the following decadal survey report, the 1972 *Astronomy and Astrophysics in the 1970s*,[30] NSF's 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 ground-based OIR telescopes. An upgrade of the VLA was recommended by the 2001 decadal survey report *Astronomy and Astrophysics in the New Millennium,*[31] 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 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

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[29] https://www.nap.edu/read/13212/chapter/1
[30] https://www.nap.edu/catalog/13231/astronomy-and-astrophysics-for-the-1970s-volume-1-report-of
[31] https://www.nap.edu/catalog/9839/astronomy-and-astrophysics-in-the-new-millennium

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 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.

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 PRC, 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 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 re-allocation 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, were awarded the opportunity to operate this telescope for FY 2016-2018. Recently they were approved for a two year extension of operations. 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 for WIYN from Pennsylvania State University an extreme precision Doppler spectrograph, NEID (NN-explore Exoplanet Investigations with Doppler spectroscopy). 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 was released in November 2017. 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 30% of its base budget.

● 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 was moved off of Kitt Peak for upgrades, then to Boulder, CO for testing, and then to Big Bear Solar Observatory. GONG is being refurbished, and the NOAA will be sharing operations costs for GONG. An interagency agreement between NSF and NOAA has already been signed.

● Sacramento Peak Telescope: A university consortium that will operate this facility is under development. The NSF funded New Mexico State University 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 FY 2016 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. The resulting competition will lead to a change of management on April 1, 2018, from the existing operators to a consortium led by the University of Central Florida with its partners, Universidad Metropolitana in San Juan and Yang Enterprises, Inc. in Oviedo.

● SOAR: The status and future of NSF support for SOAR will be reviewed after 2020.

Recommendation: The AAAC concurs with *NWNH-AMA* recommendations 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 new facilities and large projects that represent such important and substantial investments by the agencies.

Finding: NSF/AST has successfully demonstrated that it is often possible to secure partners who are capable of extending the productive scientific lifetime of NSF-developed facilities (e.g. the KPNO 2.1m and 4m telescopes) to produce excellent science while reducing the cost to NSF of operating these facilities.

Recommendation: The AAAC supports the NSF approach of working to divest from their funding portfolio aging NSF-developed facilities to partners or non-federal organizations that are able to extend the productive scientific lifetime of these facilities. This approach enables NSF/AST to redirect saved funding to the operations costs of new facilities and maintain a robust grant program.

Recommendations from "Optimizing the US Ground-based OIR Astronomy System":
As the AAAC first reported in our 2016 Annual Report, the *OIR System Report*[32] presented seven prioritized recommendations. These recommendations are beginning to be addressed by NSF/AST and the community. The second priority recommendation in the *OIR System Report* 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, 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. 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

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

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"*.[33]

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:
  ○ "Deploy a broad wavelength coverage, moderate-resolution (R = 2000 or larger) OIR spectrograph on Gemini South." Gemini has recently signed 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."

In our 2016 report we noted that we looked forward to hearing in the coming year how NSF/AST, AURA, Gemini Observatory, and NOAO might work with the community to implement the recommendations of both the *OIR System Report* and the *Maximizing Science in the Era of LSST* report. We are pleased to note this year that the proposed creation of the National Center

[33] https://www.noao.edu/meetings/lsst-oir-study/

for Optical and Near-IR Astronomy (NCOA) appears to be a possible major opportunity to enable optimization of the U.S. NSF supported facilities and a possible mechanism to further some of the goals detailed above. We look forward to seeing in the coming year how NCOA, pending final approval by NSF, is able to develop.

The AAAC commends the NSF on taking steps to support management of NOAO, Gemini, and LSST through the creation of NCOA. We anticipate that this will provide a strong basis for scientific synergies.

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

Giant Segmented Mirror Telescope (GSMT): The third highest priority of *NWNH* for federal investment in initiatives on the ground was for GSMT, 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 consortia involving US universities or institutions are undertaking projects that could match what was recommended by *NWNH.* The Giant Magellan Telescope Organization and the Thirty Meter Telescope International Observatory are both managing the fabrication and construction of their facilities. Based upon the presentations to the AAAC from NSF/AST, while we support federal participation in one or more of the possible GSMT facilities, we anticipate and support that any decisions to join one of these projects will depend on the upcoming decadal survey reaffirming that this should be a priority for federal investment.

Atmospheric Čerenkov Telescope Array (ACTA): Quoting from the AAAC 2016 report, "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): Quoting from the AAAC 2016 report, “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 of 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: As previously stated in our AAAC 2016 report and above in section 4.1, 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; 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: Efforts by AURA, NOAO, Gemini, LSST, and the proposed new NCOA to implement the recommendations of the *OIR System Report* should be supported by NSF as long as they can be accommodated while maintaining a balanced investment across the portfolio of NSF/AST.

4.3 Summary and Recommendations

The aspirations of our community inevitably exceed the budgetary constraints of NSF, DOE, and NASA. We reemphasize that to sustain US leadership in the sciences requires a balanced investment in a range of program scales and in individual investigator awards by the agencies. This will enable us to achieve our vision for the advancement of science while sustaining a robust community of researchers.

Finding: The agencies have efficiently and effectively executed the priorities of the decadal survey, given the budgetary constraints under which they are currently operating. In general their prioritization of support for projects and missions closely matches the intent of *NWNH.* The proposed termination of WFIRST, the top-ranked space-based priority from *NWNH*, in FY 2019 would be a striking exception to the way that the federal government has followed the priorities recommended by the community through the decadal survey process.

5. CMB-S4 Concept Definition Team

In November of 2016, the DOE and the NSF requested of the Chair of the AAAC that the AAAC establish a Cosmic Microwave Background Stage 4 (CMB-S4) Concept Definition Task-force (CDT) as a subcommittee of the AAAC to develop a concept for a CMB-S4 experiment. The subcommittee was formed and Dr. Charles Lawrence, Chief Scientist for Astronomy and Physics at the Jet Propulsion Laboratory, California Institute of Technology, was appointed to serve as chair of the subcommittee. The membership of the subcommittee and the details of the charge to the committee are archived on the NSF hosted web pages of the AAAC.[34]

The CDT was asked to deliver:

- A summary of the Science Requirements and their rationale
- Technical Requirements derived from the Science Requirements
- Project Strawman Concept
- Options and Alternatives (prioritized to the extent possible) for:

[34] https://www.nsf.gov/mps/ast/aaac/cmbs4cdt.jsp

    - Concept design (e.g. sites, telescopes, detectors)
    - Concept staging and schedule
    - Collaboration and Data models and interfaces
- R&D development needed, with priorities, to demonstrate technical readiness
- Cost ranges for the strawman concept, including explanations for how they were developed.

We note the CDT was not created to supplant previously existing CMB-S4 efforts. The CDT provided a mechanism for a focused design effort that drew on the considerable work of the entire CMB-S4 community to generate a report that met the needs of the agencies.

The CDT convened to begin their work at the time of the last AAAC Annual Report, March 2017, and delivered their draft report to the AAAC on 16 October 2017. The AAAC convened with Dr. Lawrence to review the report on 23 October 2017. The AAAC was responsible for reviewing both the process used by the CDT to generate their report as well as the degree to which the CDT report was responsive to its charge. At this meeting, the AAAC accepted the report as ready for delivery to the agencies.[35] The report was extensive and robust in the engagement with the broader CMB-S4 community, and clearly articulates deliverable science goals, together with two straw concept designs that could be implemented to deliver the stated science. The report was transmitted to the agencies on October 26, 2017.

Finding: The CMB-S4 Concept Definition Task-force (CDT) carried out a tremendous effort to present the science and technical requirements for CMB-S4, along with a well-thought-out concept for the CMB-S4 survey, pulling together work from the entire CMB-S4 community.

Recommendation: The AAAC commends to DOE and NSF the report of the CMB-S4 CDT, which we find clearly communicates the results of the CDT's efforts to respond to the charge they were given. We are confident that it will meet the needs of the agencies to inform funding and programmatic decisions in the near term regarding CMB-S4.

6. Preparation for 2020 Decadal Survey

6.1 General preparation informed by past experience

Planning in the community and at the federal agencies is well underway for the 2020 Decadal Survey of Astronomy and Astrophysics (DSAA). The value of this community-based effort is

[35] https://www.nsf.gov/mps/ast/aaac/cmb_s4/report/CMBS4_final_report.pdf

widely recognized by all funding agencies. The extensive process associated with such an undertaking has been streamlined and it is becoming increasingly more transparent. At this point it is essential to evaluate the interplay between the recommendations made in past DSAAs and their subsequent implementations by the funding agencies. This assessment is particularly relevant during times of shrinking or flat budgets, when the need to maintain balanced programs potentially conflicts with an understandable desire by the community to address the big science questions with large-scale projects. In this regard we draw from the 2016 Midterm Assessment of the 2010 *NWNH* Survey (*NWNH-AMA*), with a few recommendations that are relevant now, for the 2020 Decadal Survey, and beyond:

- *NWNH-AMA* recommends that independent cost estimates for projects be retained, and we find that the agencies have responded well to this recommendation.
- *NWNH-AMA* recommends that more extensive funding partnerships outside the agencies be developed. The recent NASA/ESA/JAXA collaborations on Athena, Euclid, LISA, and XARM are examples of a positive response to this recommendations.
- *NWHM-AMA* identified a misalignment between the survey outcomes generated by the Science Frontier Panels and the Project Prioritization panels. Such an alignment is critical for the task of matching capabilities (existing and to-be-developed) with the goal of addressing frontier topics. A reduced budget will make it more important than ever to align science questions and their associated ground- and space-based facilities within a balanced portfolio. Prioritization becomes more challenging, and the next Decadal Survey should address these issues through a closer interaction of frontier-oriented committee members and those who convert top science questions to top mission priorities.
- *NWNH-AMA* recommended collecting and disseminating relevant information through white papers contributed by the community. This practice is now well established and we recommend its continuation. Strategies that support this practice include dedicated Town Hall sessions at all major community meetings (AAS, APS). Representation of industry and private philanthropic organizations should be encouraged.

Finding: Strategies recommended in *NWNH-AMA* such as independent cost estimates for projects, international funding partnerships to extend scientific reach, and community outreach about the decadal survey are valuable.

Recommendation: The AAAC recommends that the next Decadal Survey process incorporate strategies that were recommended in *NWNH-AMA* to achieve project cost control, extension of scientific reach through partnerships, and community buy-in to the process.

As is often the case, recent exciting developments are likely to feed into and influence the directions considered in the Decadal Survey. The 2020 Decadal Survey will likely recognize the breakthroughs in time domain astrophysics, multi-messenger astronomy and astrophysics, and the search for planets that could potentially be habitable and will inform the agencies on how to optimize their portfolios to support these new frontier areas of research.

6.2 Upcoming Mission Concept Development

In this subsection, we turn from general preparation by the community for the next Decadal Survey, to more specific mission concept development.

CMB-S4: As described in section 5 of this report, DOE and NSF asked the AAAC in the fall of 2016 to establish a Cosmic Microwave Background Stage 4 (CMB-S4) Concept Definition Task-force (CDT) to begin the definition of CMB-S4. The final report produced by the CDT will be of great value for the next decadal survey. The CMB holds a tremendous amount of information about the early Universe as well as late-time effects due to the impact of cosmic structure growth on the CMB, and the AAAC recognizes the outstanding value future investigations of the CMB will have on our most fundamental questions about cosmology. Our Findings and Recommendations regarding CMB-S4 are in section 5.

Planning for future ground-based facilities: NSF, AUI, and AURA are all working, together with non-profit foundations, Universities, and members of the community, to study science cases and science capabilities that should be considered by the next Decadal Survey. An incomplete, but representative list of meetings contributing to this process include *U.S. Radio/Millimeter/Submillimeter Science Futures in the 2020s; NOAO 2020; Big Questions, Big Surveys, Big Data: Nighttime Astronomy and Cosmology in the 2020s (SnowPAC 2018);* and others aimed to inform the next Decadal Survey.

Finding: The AAAC applauds the efforts of the NSF, AUI, AURA, and the NSF's observatories to work with the community to help prepare for the upcoming Decadal Survey through their support of meetings and studies designed to investigate science cases, science capabilities, and facilities for consideration by the Decadal Survey.

Future NASA mission concepts: In 2015 NASA commissioned the *Enduring Quests and Daring Visions,* a 30-year roadmap.[36] This planning exercise for long-term development of NASA Astrophysics identified notional surveyor mission concepts in the context of three fundamental questions: Are we alone? How did we get here? How does the Universe work? In response to the goals identified in that report, NASA developed four major Science and Technology Definition Teams. Mission concepts that flowed from those efforts include: an infrared telescope (Origins Space Telescope); an exoplanet characterization telescope (HabEx);

[36] http://go.nasa.gov/1gGVkZY

a UV/Optical/Infrared telescope (LUVOIR); and an X-ray telescope (Lynx). The results of these extensive studies will flow into the 2020 Decadal Survey.

NASA is also supporting ten Probe Class mission studies for submission to the decadal survey.[37] NASA intends that the Decadal Survey Committee will have the option to prioritize any of the submitted mission concepts, or recommend a competed line of Probes, similar to Explorers.

Assessing the utility of CubeSats for scientific research: Beginning in 2017, NASA Astrophysics Division R&A contains 5 million dollars per year for CubeSat development. Two missions are currently in development. This pilot program serves to determine if CubeSat missions could have astrophysics science utility.

Recommendation: The AAAC supports the NASA Astrophysics Division CubeSat initiative and recommends it continue to execute Announcements of Opportunity to determine the viability of CubeSats as a valuable component of NASA's efforts in astrophysics.

Finding: The AAAC applauds NASA's efforts to support, working with the community and NASA Centers, the development of well-studied and costed mission concepts for consideration by the Decadal Survey.

6.3 Impact of the Decadal Survey Process

Innumerable examples of US frontier scientific leadership in astronomy and astrophysics demonstrate that the process of evaluating the state of the profession and developing long term vision with associated concrete plans for science and technology development on a 10-year cycle is an excellent method to inform the funding agencies, and to guide their collaborative enterprises. The physics and astronomy communities greatly value the Decadal Survey process and appreciate opportunities to contribute to it (via service on committees and offering input through white papers, or participating in extensive mission studies). The many discoveries made in this golden era of scientific exploration are in large part the result of a process that engages the community to dream while simultaneously creating financially realistic recommendations. We applaud the funding agencies and the community for their commitment to these principles.

Finding: The AAAC finds that the Decadal Survey process, including implementation of the recommendations by the agencies, is important for ensuring that the US remains a global leader in scientific exploration and technology development.

[37] https://smd-prod.s3.amazonaws.com/science-pink/s3fs-public/atoms/files/ProbeStudies_Management_and_Processv1-1%20TAGGED.pdf

7. Budget Summary and Impact

FY 2018 Budget Status and Plans for FY 2019: In FY 2018, there have thus far been five continuing resolutions and two government shutdowns. For NASA, NSF, and DOE this uncertainty in their current operating budgets adversely and substantially impacts the management of large projects. This is especially true when actual spending authority only becomes known with half of the fiscal year, or less, remaining. Major program redirections and replanning becomes highly inefficient under such circumstances.

As this report was in preparation, two significant changes to the budget landscape occurred. First, Congress enacted a bipartisan budget agreement which raised the statutory caps on discretionary spending for FY 2018 and FY 2019. This action substantially relieves the threat of sequestration that would have otherwise occurred in both years. This same agreement extended current spending levels in FY 2018 to March 23, beyond the submission date for this report. Thus some issues noted by the AAAC will not have been resolved.

The second major change to the budget landscape is associated with the President's requested budget for FY 2019. In the administration's submission, they proposed a partial allocation of the discretionary spending under the newly established caps, with the remainder at the discretion of Congress. In this report we address the remaining issues in FY 2018, and some preliminary observations concerning the FY 2019 budget request.

The FY 2018 budget for NASA Astrophysics was intended to be a balanced program of small, medium, and large missions all of which are essential to NASA's mission and have strong connections to NSF and DOE astrophysics. The overall budget relevant to the charge of the AAAC is dominated by the base program, the declining budget for the James Webb Space Telescope, and the WFIRST development program. Together these provide a planning wedge beginning in FY 2020 that will allow NASA to continue a robust astrophysics program.

As we finalize our report in mid March of 2018, both the House and Senate FY 2018 appropriations bills fund NASA at a level that would enable NASA to support a balanced program and make progress on the highest *NWNH* recommendations for space. However, in presentations to the AAAC from NASA in January 2018, we learned that the combination of directives and specified program funding in the two bills could result in a reduction of over $53 million in those portions of the astrophysics portfolio that were not specifically addressed as line items. Absorbing this reduction in the half year remaining could be extremely difficult, leading to either inefficient application or waste of resources. We are hopeful that the bill that emerges from the conference committee and is passed will have found a way to avoid asking NASA to deal with such a challenge.

For NSF, both House and Senate bills have proposed a partial restoration of reductions proposed in the FY 2018 budget request. The range of outcomes remains large however and any overall reductions to the NSF would need to be allocated to each directorate and division. For NSF, the most substantial budget issue in future planning is to phase in the operations funding for DKIST and LSST while at the same time divesting and reducing cost to NSF in current facilities. Planning for DKIST operations is mostly complete. The next major challenge will be to accommodate the NSF share of LSST operations without unbalancing the astronomy division portfolio or adversely impacting awarded grants. At the time of the AAAC meeting in January 2018, the NSF had received a formal proposal for LSST operations that, after review, will be submitted to the National Science Board for final approval.

For DOE, budget planning has followed the 2014 P5 Strategic Plan which contains an upper and lower funding profile. At the higher profile, Scenario B, the full range of programs would be enabled which include participation in the Large Hadron Collider, construction of the Long Baseline Neutrino Facility, and the Cosmic Frontier program under the purview of the AAAC . At the lower profile, Scenario A, executing the full array of planned activities within High Energy Physics would be extremely challenging. Although the President's request for FY 2018 was significantly below Scenario A, both the House and Senate Appropriations bills would provide HEP funding above Scenario B. This is a major issue that will need to be resolved as part of the full year FY 2018 appropriations.

Finding: Delays in passing the appropriations for the agencies for a given FY that extend well into that FY, often accompanied by temporary levels of funding provided by a continuing resolution, may create severe challenges and added risks for the efficient management of programs, missions, facilities, and the award of research grants. If the subsequent appropriation levels require significant cuts to missions or facilities, absorbing the reduction during the remainder of the FY is likely to be extremely difficult, leading to either inefficient application or waste of resources.

FY 2019 Budget Concerns: The President's requested budget for FY 2019 contains two proposals of great concern to the AAAC. The budget for NASA would cancel the WFIRST program, the highest space-based priority in the 2010 Decadal Survey, *NWNH*. WFIRST addresses major scientific themes detailed in section 4.1 above. Cancelling WFIRST would be a substantial departure from the vision of *NWNH.*

The *WFIRST Independent External Technical/Management/Cost Review (WIETR)* found that the life-cycle cost from the KDP-A agreement ($3.2B) was inconsistent with the scope, requirements, and the appropriate risk classification for the mission. Therefore, NASA directed the WFIRST Project to find cost savings to fit within the $3.2B cost cap prior to the decision point for entering Phase B. The AAAC was informed, through briefings by NASA, of a detailed list of descopes and other changes necessary to bring the total mission cost back to the $3.2B cost cap set at the beginning of Phase A in 2016. While the AAAC understands the challenges of prioritizing programs within a constrained budget, as we discuss in detail in section 4.1, we urge Congress to increase the appropriation for NASA, enabling NASA and the administration to maintain their past support for the highest priority of *NWNH* for a new space initiative, allow a balanced program within NASA astrophysics, and still enable the President's new initiatives.

Recommendation: The AAAC urges Congress to increase the proposed FY 2019 appropriation for NASA above the President's request, enabling NASA and the administration to maintain their past support for the highest priority of *NWNH* for a new space initiative (NASA's Wide-Field Infrared Survey Telescope, WFIRST), allow a balanced program within NASA astrophysics, and still enable the President's proposed new initiatives for NASA.

The second issue of concern is that the proposed FY 2019 budget for DOE High Energy Physics falls at the lower boundary of the P5 scenarios. It would be a challenge under the proposed budget for DOE to continue planning for the existing Major Items of Equipment in development (Dark Energy Spectroscopic Instrument, LSSTCam, SuperCDMS-SNOLAB and LZ) while maintaining an adequate grants program. The overall pattern for the Administration's requested funding for High Energy Physics in FY 2018 and 2019 suggests a substantial decline in the out years compared to the modest sustained increases recommended by P5. The AAAC was informed that the Major Items of Equipment now in the HEP portfolio can be maintained up through FY 2019. However, the ability to fund extramural grants will be challenging, and the ability to maintain future progress is uncertain.

Finding: The AAAC is concerned that the proposed FY 2019 budget for DOE High Energy Physics falls at the lower boundary of the scenarios considered by P5. We note that it would be a challenge at this level of appropriations for DOE to continue planning for the existing Major Items of Equipment in development (Dark Energy Spectroscopic Instrument, LSSTCam, SuperCDMS-SNOLAB and LZ) while maintaining an adequate grants program.

Attempts to address research grant oversubscription: For both FY 2018 and FY 2019, the AAAC calls attention to the funding for individual investigator research grants, and research and analysis funding. The AAAC has noted in the past the enormous cost to the community associated with proposal writing for programs that are vastly oversubscribed. The AAAC recognizes the efforts made by the funding agencies to address this issue.

The AAAC has followed with great interest the NSF experiment to phase in no-deadline proposal calls. Preliminary evidence suggests that this change will reduce the oversubscription ratio and reduce workload on the community. Similarly, NASA has implemented its own strategy to reduce proposal pressure, dropping the Astrophysics Theory Program to calls every other year (without reducing funding). The AAAC urges that these, and other means, to address the oversubscription ratio continue, with careful evaluation of whether these strategies are addressing the problem without adverse consequences to the community.

Recommendation: NSF and NASA should continue to carry out and evaluate their strategies for reducing proposal pressure, reporting to the community for feedback on their evaluation strategies and the results.

AAAC report timing: Finally, the AAAC notes that this year, as has been the case in the recent past, the committee is requested to meet, formulate its recommendations, and submit a report by the statutory date of March 15. Given the rapidly shifting and uncertain budget scenarios, it is often the case that the report of the AAAC is not fully informed by important budget developments. The AAAC wishes to fully fulfill its charter and provide timely and meaningful recommendations. In order to do so, a change to the statutory due date would be extremely helpful. Generally, a due date of, for example, 45-60 days following the submission of the President's budget, would provide sufficient time for the AAAC to fully interact with the funding agencies and formulate its recommendations.

Finding: The statutory deadline, March 15th, for the submission of the AAAC annual report does not allow sufficient time for the committee to react to budget developments that typically occur in the first two months of each calendar year.

Recommendation: The AAAC recommends that the annual report deadline be changed from a fixed date to a deadline 45-60 days following the submission of the President's budget request, so as to enable sufficient opportunity for the committee to interact with the funding agencies, understand the impact of the President's budget, and formulate recommendations. The AAAC would endeavor to still meet the current deadline of March 15th when possible.

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
AO	Adaptive Optics or Announcement of Opportunity
APS	American Physical Society
ATI	Advanced Technologies and Instrumentation
AUI	Associated Universities, Inc.
AURA	Association of Universities for Research in Astronomy, Inc.
ADMX	Axion Dark Matter eXperiment
ADMX-G2	Axion Dark Matter eXperiment - Generation 2
BAO	Baryon Acoustic Oscillations

BASS	Beijing-Arizona Sky Survey
CAA	Committee on Astronomy and Astrophysics
CASE	Contribution to ARIEL Spectroscopy of Exoplanets
CCAT	Cerro Chajnantor Atacama Telescope
CD	Critical Design review
CDT	Concept Definition Task Force
CFHT	Canada-France-Hawaii Telescope
CORF	Committee on Radio Frequencies
COSI-X	Compton Spectrometer and Imager Explorer
CMB	Cosmic Microwave Background Radiation
CMB-S4	Cosmic Microwave Background - Stage 4 (experiment)
CTA (or ACTA)	Atmospheric Čerenkov Telescope Array
DECaLS	DECam Legacy Survey
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
DOE/HEP	Department of Energy High Energy Physics
DR1	Data Release 1
DR5	Data Release 5
DSN	Deep Space Network
eBOSS	Extended Baryon Oscillation Spectroscopic Survey
EC	Euclid Consortium
EIS	Environmental Impact Statement
EMS	Electro Magnetic Spectrum
ESA	European Space Agency
ESO	European Southern Observatory
FACA	Federal Advisory Committee Act
FINESSE	Fast Infrared Exoplanet Spectroscopy Survey Explorer
FCC	Federal Communications Commission
FDR	Final Design Review
FEMA	Federal Emergency Management Agency
Fermi-LAT	Fermi Large Area Telescope
FY	Fiscal Year
GBT	Green Bank Telescope
GEO/AGS	Geosciences Directorate/Division of Atmospheric and Geospace Sciences
GONG	Global Oscillation Network Group
GRB	Gamma Ray Burst
GSMT	Giant Segmented Mirror Telescope
GUSTO	Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory

HCT	Himalayan Chandra Telescope
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel
ISS-TAO	International Space Station - Transient Astrophysics Observer
IXO	International X-ray Observatory
IXPE	Imaging X-Ray Polarimetry Explorer
JAXA	Japan Aerospace Exploration Agency
JVLA	Jansky Very Large Array
JWST	James Webb Space Telescope
KPNO	Kitt Peak National Observatory
LED	Light Emitting Diodes
LIGO	Laser Interferometer Gravitational-Wave Observatory
LIGO-Virgo (collaboration)	Laser Interferometer Gravitational-Wave Observatory-Virgo
LISA	Laser Interferometer Space Antenna
LPS	LISA Preparatory Science
LST	LISA Study Team
LSST	Large Synoptic Survey Telescope
LZ	LUX-Zeplin
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescopes
MIDEX	Medium-Class Explorers
MOA	Memorandum of Agreement
MO	Mission of Opportunity
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
MzLS	Mayall z-band Legacy Survey
NAOJ	National Astronomy Observatory of Japan
NASA	National Aeronautics and Space Administration
NASA/APD	National Aeronautics and Space Administration Astrophysics Division
NCOA	National Center for Optical and Near-IR Astronomy
NEID	NN-explore Exoplanet Investigations with Doppler spectroscopy
NICER	Neutron Star Interior Composition Explorer
NN-EXPLORE	NASA-NSF Exoplanet Observational Research
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRO	National Reconnaissance Office
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
NTIA	National Telecommunications and Information Administration
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
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System
PRC	National Science Foundation Portfolio Review Committee
R&D	Research and Development
ROSES	Research Opportunities in Space and Earth Science
SDSS	Sloan Digital Sky Survey
SEXTANT	Station Explorer for X-ray Timing and Navigation Technology
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
SMEX	Small Explorers Missions
SPHEREx	Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer
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
ULDB	Ultralong-Duration Balloon
URO	University Radio Observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLT	Very Large Telescope
WFIRST	Wide-Field Infrared Survey Telescope
WIETR	WFIRST Independent External Technical/Management/Cost Review
WIMPS	Weakly Interacting Massive ParticleS

WISE Wide-field Infrared Survey Explorer

WIYN Telescope or Consortium (Originally referring to University of Wisconsin, Indiana University, Yale University, and the National Optical Astronomy Observatory, the original members of the consortium that built and operated a 3.5m telescope on Kitt Peak. Yale University is no longer part of the consortium, but the University of Missouri has joined.)

XARM X-ray Astronomy Recovery Mission

XRP Exoplanet Research Program