W. M. KECK OBSERVATORY
Maunakea, Island of Hawai`i

April 28, 2019

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

Mr. James Bridenstine, 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 Eddie Bernice Johnson, Chairwoman
Committee on Science, Space and Technology
United States House of Representatives
Washington, DC 20515

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

The Honorable Lamar Alexander, Chairman
Committee on Health, Education, Labor & Pensions
United States Senate
Washington, DC 20510

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Dear Dr. Córdova, Mr. Bridenstine, Secretary Perry, Chairwoman Johnson, Chairman Wicker, and Chairman Alexander:

I am pleased to transmit to you the annual report of the Astronomy and Astrophysics Advisory Committee for 2018. As you are aware, this year's report was delayed due to the partial government shutdown early in 2019. The Committee thanks you for your patience, and apologizes for the delay in sending the report.

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 sixteenth 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.

If there are any matters your offices would like AAAC input on in addition to this report, I would be glad to provide you with a personal briefing.

Sincerely yours, on behalf of the Committee,

Dr. John O'Meara
Chair, Astronomy and Astrophysics Advisory Committee

cc:
Representative Frank Lucas, Ranking Member, Committee on Science, Space, and Technology, United States House of Representatives
Senator Maria Cantwell, Ranking Member, Committee on Commerce, Science and Transportation, United States Senate
Senator Patty Murray, Ranking Member, Committee on Health, Education, Labor & Pensions, United States Senate
Senator Jerry Moran, 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

Senator Lisa Murkowski, Chairwoman, Committee on Energy & Natural Resources, United States Senate
Senator Joseph Manchin, Ranking Member, Committee on Energy & Natural Resources, United States Senate
Representative Bobby L. Rush, Chairman, Committee on Energy and Commerce, Subcommittee on Energy
Representative Fred Upton, Ranking Member, Committee on Energy and Commerce, Subcommittee on Energy
Representative José Serrano, Chairman, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives
Representative Robert Aderholt, 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 Marcy Kaptur, Chairwoman, Subcommittee on Energy and Water Development and Related Agencies, Committee on Appropriations, United States House of Representatives
Representative Mike Simpson, Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, United States House of Representatives
Dr. F. Fleming Crim, 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
Mr. Gabriel Adler, Office of Legislative Affairs, National Aeronautics and Space Administration
Dr. J. Stephen Binkley, 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
Ms. Amanda Greenwell, Head, Office of Legislative and Public Affairs, National Science Foundation
Ms. Karen Pearce, Senior Legislative Affairs Specialist, Office of Legislative and Public Affairs, National Science Foundation

Astronomy and Astrophysics Advisory Committee Members:

Dr. Rachel Bean, Cornell University
Dr. Andrew Connolly, University of Washington
Dr. Ian Dell'Antonio, Brown University
Dr. Scott Dodelson, Carnegie-Mellon University
Dr. Dieter Hartmann, Clemson University
Dr. Kelsey Johnson, University of Virginia
Dr. Mansi Kasliwal, California Institute of Technology
Dr. Brian Keating, University of California, San Diego
Dr. Eliza Kempton, University of Maryland
Dr. Shane Larson, Northwestern University
Dr. Petrus Martens, Georgia State University
Dr. John O'Meara, W.M. Keck Observatory
Dr. Constance Rockosi, University of California, Santa Cruz

Report of the Astronomy and Astrophysics Advisory Committee

April 26, 2019

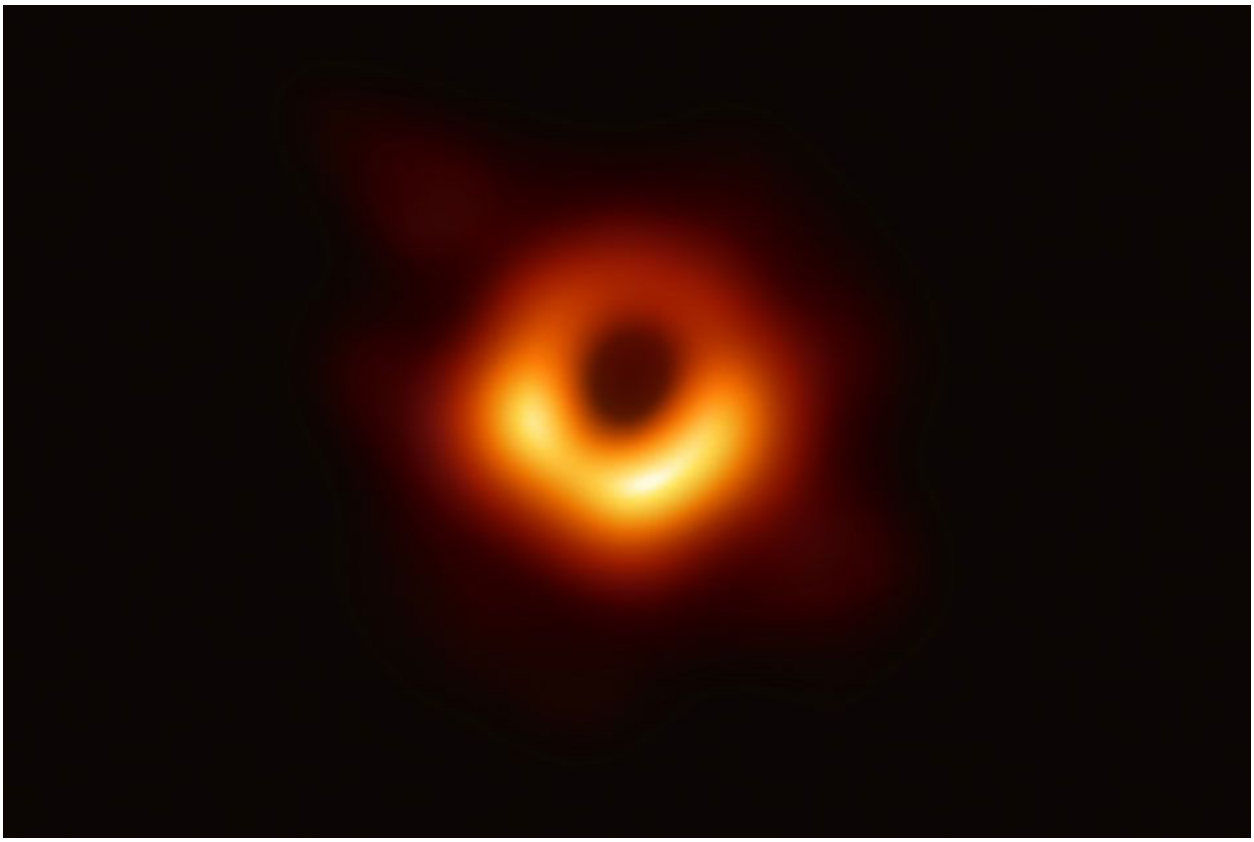

Image credit: Event Horizon Telescope Collaboration

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Executive Summary

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.

Collected Findings and Recommendations

1. Finding: The continuing US investment in fundamental research by DOE, NASA, and NSF 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.

2. Finding: NSF, NASA, and DOE continue to work well together to support the needs and priorities of the astronomy and astrophysics community, both through coordination of research programs and collaboration on large managed projects.

3. 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. In addition, 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.

4. 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.

5. Recommendation: All current and planned surveys supported by NSF, NASA and DOE/Cosmic Frontier 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 endeavor to use open source code to create the data products in order that the community can learn how those data products were created. We are aware that support for continued use of the source code is a much larger endeavor, and the additional benefit of such support is not clear at this time. Agencies should include in survey budgets funding to enable adequate public access to the data, software, and data products of these surveys.

6. Recommendation: The three agencies should coordinate on the guidelines and expectations for the public 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.

7. Finding: The agencies have made multi-billion dollar investments in astronomical telescopes, satellites, and experiments over the last decade. These world class facilities will impact our understanding of the universe for decades to come, providing a resource for many generations of scientists. The scientific value of the data these observatories will generate often exceeds the lifetime of the mission itself. While NASA has a history of preserving data well beyond the lifetime of the mission, NSF/AST does not have a policy for investing in long-term data curation. The AAAC recognizes the need to preserve and serve astronomical data sets well beyond the lifetime of a mission or program.

8. Recommendation: The AAAC recommends that NSF develop a policy to support the archiving and distribution of data sets generated by large and mid-scale observatories beyond the lifetime of the individual experiments. Ideally, this policy would include interoperability with existing archives. This policy will principally apply to the data products from public surveys and will require the periodic evaluation of the value of extant data sets, to ensure that resources are efficiently allocated.

9. Finding: The issue of public release of data sets, data products, data access tools, and related software is a complicated and rapidly evolving one. A review and update of the the AAAC Principles of Access is warranted.

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

11. Recommendation: We continue to 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.

12. Finding: Competing interests continue to provide a severe and unrelenting threat to astronomers' ability to detect electromagnetic signals from space. Without clean access to these wavelengths, the ability of astronomers to obtain fundamental knowledge about the universe is profoundly impaired. This is particularly important as time-variable astronomy gains visibility (for example in detecting gravitational wave counterparts or other multi-messenger astronomy activities). Mobile and transient noise sources form a large and growing threat.

13. 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.

14. Recommendation: Given their common interests in access to the spectrum, 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.

15. 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. Efforts to engage and coordinate with other international agencies should continue.

16. Finding: NASA's Wide Field Infrared Survey Telescope (WFIRST) as approved to enter phase B would deliver the science identified for the version of WFIRST recommended in NWNH and provide an important technology demonstrator for future coronagraphic missions.

17. Recommendation: The AAAC continues to recommend ongoing cost assessment and mission review of the Wide Field Infrared Survey Telescope (WFIRST) prior to and after Preliminary Design Review.

18. Finding: The President's requested level of FY 2020 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).

19. Finding: The proposed termination of WFIRST, as presented in the President's requested FY 2020 budget for the astrophysics division of NASA, would result in the withdrawal of federal support for the highest ranked priority for space from *NWNH.*

20. 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.

21. 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.

22. 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 President's 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.

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

24. Finding: The AAAC commends the NASA Astrophysics Division on fulfilling the recommendation of *NWNH* and *NWNH-AMA* that at least four Announcements of Opportunity for the Explorer program be executed this decade. The Explorer program has provided and continues to provide a valuable complement of agile, low-cost missions in space to the NASA portfolio.

25. Finding: NASA's TESS mission is performing at or beyond its expected level and is currently well on its way toward meeting its level-1 science requirements. The AAAC notes that the exoplanet mass measurements required to meet the TESS level-1 science requirements are only partly funded by NASA and NSF efforts, with the rest coming from private and/or international resources.

26. Finding: The AAAC recognizes that NASA's space mission portfolio has great potential for supporting the emergent area of multi-messenger astrophysics that has been opened by the NSF supported observations of gravity waves. 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, as well as Laboratory Astrophysics.

27. Finding: JWST remains an essential component of the astrophysical science landscape. The observatory is currently on track for a 2021 launch.

28. Recommendation: NASA should continue to allocate resources to successfully launch JWST at the earliest possible date.

29. Recommendation: The AAAC recommends to Congress that SOFIA's prime mission be considered complete at the end of FY2019, and that SOFIA undergo senior review in the next regular review cycle, in line with normal NASA review procedures.

30. 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.

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

32. Finding: The AAAC appreciates and supports the work by NSF/AST to develop and sustain the Mid-Scale Innovations Program (MSIP). The projects supported by this program are beginning to produce exciting scientific returns for the astrophysics community.

33. Recommendation: NSF/AST should continue to grow and develop the MSIP program in the context of a balanced portfolio. Care should taken to evaluate the progress and management of these programs after the award and to ensure that the promises for community access to the facilities and data are realized. NSF/AST should review the impact of community access to MSIP funded programs periodically throughout the life of the award.

34. Finding: The AAAC is pleased to see the development of the Mid-Scale Research Infrastructure program (MSRI). The very large number of proposals that were submitted in response to the initial call demonstrates the significant need within the science and engineering community for renewed infrastructure to support ongoing and future science programs.

35. Recommendation: NSF/AST should ensure that the astronomical community is aware of the MSRI opportunities and in particular the range of infrastructure projects that can be supported by this program.

36. Finding: Alternatives to the standard (WIMP) dark matter scenario can be explored in a wide variety of ways, and the community is devoting time and resources to develop new search techniques. DOE-HEP set up a Basic Research Needs group to assess the landscape. There are potential synergies with exciting developments in the area of quantum sensors.

37. Finding: The AAAC Commends the DES team, DOE, and NSF for successfully completing DES operations and for transferring DECam to become a community instrument

38. Recommendation: DOE-HEP should continue to pursue searches for alternatives to the standard dark matter candidates.

39. 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 to produce excellent science while reducing or eliminating the cost to NSF of operating these facilities.

40. Recommendation: The AAAC recommendations that the NSF facility divestment process be completed 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.

41. 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.

42. Recommendation: Efforts by AURA, and 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.

43. 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 cessation of WFIRST (top-ranked space-based priority from *NWNH*) in FY 2020 would be a striking exception to the way that the federal government previously followed the priorities recommended by the community through the decadal survey process.

44. Finding: the AAAC finds that the GBS subcommittee report addresses the charge questions and provides an evaluation of the important role of the GBS telescopes in the US system in the first part of the next decade.

45. Recommendation: the NSF should work towards implementing the recommendations of the GBS subcommittee, particularly those that affect the impact of the GBS system over the next ~5 years, before the Decadal Survey recommendations take precedence.

46. 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.

47. Finding: The agencies have responded appropriately to the NWNH-AMA recommendations regarding independent cost assessment.

48. Finding: Recent collaborations between NASA and international partners on Athena, Euclid, XRISM, and LISA further the recommendations of NWNH and NWNH-AMA.

49. 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.

50. Recommendation: The AAAC recommends that the next Decadal Survey continue to obtain input from the community through white papers and direct engagement. The AAAC further recommend that the Decadal Survey make every attempt to engage all members of the astronomical community (including industrial partners, international partners, and philanthropic organizations) and pay particular attention to obtaining input and panel membership from as diverse a spectrum of the community as possible.

51. Finding: We find that the Decadal Survey process is important for ensuring that the US remains a global leader in scientific exploration and technology development.

52. Finding: The funding levels appropriated by Congress in the FY 2018 and FY 2019 budgets generally positively impacted all three agencies' ability to meet the recommendations of *NWNH*

53. Finding: Delays in passing the appropriations for the agencies for FY 2019 create challenges and added risks for the efficient management of programs, missions, facilities, and the award of research grants.

54. Finding: Protracted periods of government shutdown have significant negative impact on the short-term ability for the agencies to manage programs and portfolios. Additionally, they create additional risk for personnel loss at the agencies, creating further strain on the agencies' ability to perform their missions.

55. Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for NASA above the Administration's request to continue to provide a balanced program within astrophysics in line with the recommendations of *NWNH*.

56. Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for NSF above the Administration's request to enable the Agency to properly balance research and infrastructure funding needs to meet the recommendations of *NWNH*.

57. Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for DOE High Energy Physics above the Administration's request to provide adequate funding for operations of and research and analysis of data from from the numerous world-class facilities currently nearing completion.

58. 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.

59. 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, 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[1] (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*[2] *(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 2018-2019 committee reviewing activities in 2018 and early 2019.

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 2018-2019, the image of the supermassive black hole named Powehi at the center of the elliptical galaxy M87 obtained by the Event Horizon Telescope.

Since March 15, 2018, the AAAC has had four meetings, two in-person, two via teleconference. The January 2019 meeting was rescheduled to February 2019 due to the partial government shutdown. Representatives of the three agencies have given briefings and provided input on the status of their programs. As we finalize this report, the FY 2019 appropriations have been announced, and the FY 2020 budget request has been submitted by the Administration.

The AAAC notes that some sections repeat discussion, findings, and recommendations of reports from previous years. The committee continues to find these discussions of importance, and continues to support the findings and recommendations made.

2. Highlights of 2018-2019

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.

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[1] https://www.nsf.gov/mps/ast/aaac.jsp
[2] https://www.nap.edu/catalog/12951/new-worlds-new-horizons-in-astronomy-and-astrophysics

Finding: The continuing US investment in fundamental research by DOE, NASA, and NSF 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.

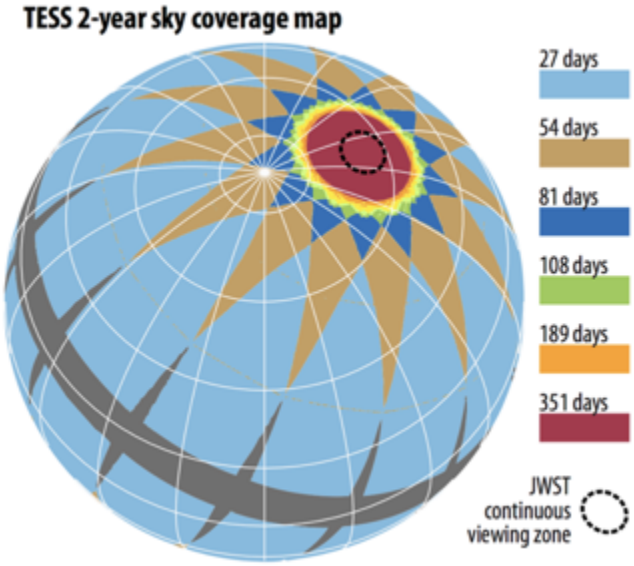
TESS launch and successful start of mission

NASA's Mid-Size Explorer, TESS (The Transiting Exoplanet Survey Satellite), successfully launched on April 18, 2018 aboard a SpaceX Falcon 9 rocket. TESS will complete a full-sky survey to find exoplanets orbiting the brightest stars in the night sky over a 2-year time period. The planets that TESS is expected to discover will be some of the very best targets for atmospheric studies with HST and JWST. Additional support of TESS Exoplanet science is provided by NASA's Neil Gehrels Swift Observatory, which monitors UV/X-ray variability of stars that hst planets, allowing an assessment of habitability. Swift-UVOT detected its first exoplanet transit (in WASP-121 b), providing information on ionized iron in an extended atmosphere. Ground-based follow-up to TESS discoveries will allow us to measure the masses of many small planets and to determine whether these are rocky planets, like the Earth. The TESS mission is currently meeting or exceeding all of its performance expectations. So far, TESS has discovered 10 new exoplanets as well as close to 500 additional planet candidates, many of which are likely to be confirmed as exoplanets. In addition to exoplanets, TESS has exquisite early-time light curves of 18 Type Ia supernovae placing strong constraints on the single degenerate progenitor channel. As of the writing of this report, TESS is approximately 3 months away from completing its survey of the southern hemisphere, at which time it will flip to surveying the northern hemisphere for the upcoming year. TESS follow-up observations from the ground are ongoing, and will be a focus of the NEID spectrograph, which is being built under a partnership between NASA and NSF.

On April 16th TESS announced the discovery of its first Earth-size planet, HD21749c. This planet, with an 8-day orbital period, is about 89% the diameter of the Earth. It orbits a K-type star that is a distance of 52 light years from the Earth and in the southern constellation Reticulum.

NASA's TESS mission launched successfully on April 18, 2018 aboard a SpaceX Falcon 9 rocket. The image on the right is one of the first light images released by TESS showing the

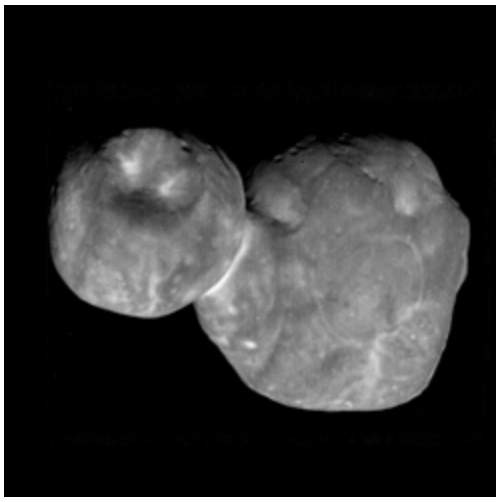
Large Magellanic Cloud and the star R Doradus. Image credits: Fortune Magazine — http://fortune.com/2018/04/15/nasa-spacex-tess-planet-hunter/ and NASA/MIT/TESS



Caption: TESS will survey the entire sky to search for exoplanets and other astrophysical transients.
Image credit: https://tess.mit.edu/

New Horizons Flyby of Ultima Thule

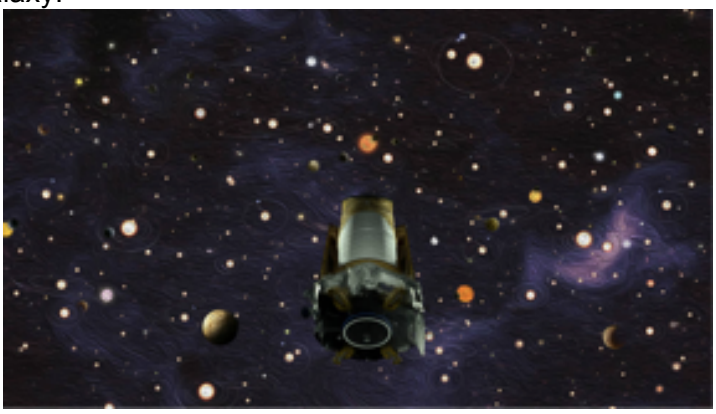
NASA's New Horizons mission flew past the Kuiper Belt object Ultima Thule at 12:33 a.m. (EST) on January 1, 2019. Ultima Thule is the most distant object to have ever been visited by a human-made spacecraft. The Ultima Thule flyby is also notable in representing the highest navigation precision ever achieved by any spacecraft before. As a Kuiper Belt object, Ultima Thule is most likely one of the pristine remnants leftover from the formation of our solar system and therefore provides clues as to the conditions and history of this event. The images obtained are of spectacular quality and show an intriguing shape — that of a "contact binary", which points to Ultima Thule having undergone a very slow speed collision in its distant past. It's two lobes are fused together giving it the approximate shape of a peanut.



Caption: Ultima Thule, a contact binary Kuiper Belt object imaged by NASA's Deep Horizons mission.
Image credit: NASA — https://solarsystem.nasa.gov/news/860/new-horizons-spacecraft-returns-its-sharpest-views-of-ultima-thule/

Kepler End of Mission

NASA's Kepler satellite ran out of fuel on October 20, 2018, signaling the end of the mission. Launched in 2009, Kepler was initially envisioned as a 3-year planet hunting mission searching for transiting planets orbiting 150,000 stars all located in one small patch of the sky. When, four years into the Kepler mission, mechanical failures brought the prime planet-hunting pursuit to an end, the Kepler spacecraft was repurposed as K2. The K2 mission surveyed a larger portion of the sky, albeit piecewise for shorter periods of time, using the force exerted by the solar wind to aid in precisely pointing the telescope. Over its 9 year duration, the Kepler mission discovered over 2,500 exoplanets and fundamentally changed our understanding of the population of planets within our galaxy.



Caption: An artist's rendition of the Kepler spacecraft and the plethora of planetary systems it discovered. Image credit: Credits: NASA/Wendy Stenzel — https://www.nasa.gov/press-

release/nasa-retires-kepler-space-telescope-passes-planet-hunting-torch

Event Horizon Telescope Images Supermassive Black Hole
On April 10, 2019, the Event Horizon telescope (EHT), a global collaboration of eight radio telescopes including ALMA, revealed an image of the accreting supermassive black hole in Messier 87. The unprecedented spatial resolution of the ring-like image gives a precise radius of the event horizon and hence, precise mass of the supermassive black hole. It confirms predictions by Einstein's theory of general relativity. It is a feat in large-scale computing. EHT was funded by the NSF MSIP program.

Caption: The first image of a black hole in the galaxy M87 taken by the Event Horizon Telescope. Credit: the Event Horizon Telescope Collaboration

Highlights in Time-domain Astronomy in preparation for LSST
Starting June 2018, the Zwicky Transient Facility (ZTF) started publicly releasing ~100,000 alerts on new transient/variable/moving events in LSST format. This discovery stream has mobilized multiple event brokers preparing for the LSST era including ANTARES, ALERCE, LASAIR and MARS. ZTF discoveries are now being followed up by multiple teams and telescopes worldwide. ZTF was also funded by the NSF MSIP program.

AT2018cow
A mysterious, rapidly evolving, relativistic explosion discovered by the ATLAS survey was extensively followed up by a worldwide network of ground based as well as space-based observatories. The emission appears to be powered by a central engine, possibly the birth of a highly magnetized neutron star (magnetar) or a stellar-mass black hole.

Dark Energy Survey Completes Six-Year Mission
On January 9, 2019, the dark energy survey completed collecting data with the Dark Energy

Camera (DECam) on the CTIO-4m Blanco telescope concluding its six-year mission. This sensitive map of 300 million distant galaxies and over 50 Tb of data has already led to over 200 refereed journal publications. Highlights include the most precise measurement of dark matter structure, discovering many more dwarf galaxies and identifying the most distant supernovae. There has also been a public data release of the first three years of data. The Dark Energy Survey is a joint NSF-DOE program, and DECam was funded by DOE.

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. The astronomical community has been preparing for the next chapter in multi-messenger astrophysics, awaiting the start of the next phase of LIGO operations. The extended Baryon Oscillation Spectroscopic Survey (eBOSS) and the Dark Energy Survey (DES) both completed observations this year and are preparing the science analysis of their full samples. Construction is proceeding on their successors, the Dark Energy Spectroscopic Instrument (DESI) and the Large Synoptic Survey Telescope (LSST), with DESI achieving the first on-sky images with its wide-field corrector in April, 2019. 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. Study of the Cosmic Microwave Background (CMB) is a long-standing area of cooperation between the agencies. The DOE and NSF are coordinating with the CMB-S4 collaboration and pre-Project Design Group as CMB-S4 moves through concept planning, and for providing input to the Decadal survey. Inter-agency coordination of the major project milestones (the CD phases for the DOE and the NSF-MREFC design reviews) is highly encouraged to keep the project moving forward toward construction. 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 are also collaborating on decadal survey sponsorship, coordinated ground-space observations, detection of Near Earth Objects, the exoplanet research program and many others.

Finding: NSF, NASA, and DOE continue to work well together to support the needs and priorities of the astronomy and astrophysics community, both through coordination of research programs and collaboration on large managed projects.

3.2 Opportunities for Future Coordination and Collaboration

In addition to the collaborative efforts mentioned above and those in progress or proposed in section 4, we highlight here important opportunities for collaboration that are consistent with the ongoing efforts of all the agencies, but which are highlighted here because they do not map perfectly into our discussions in section 4. These include efforts to broaden the impact of and the lasting availability 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.

Ensuring 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 to generate 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 the data and data products for the broader astronomical community have consistently and significantly outweighed the cost of providing 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. These data releases, and 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. In addition, 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.

At the moment, individual agencies (for example NASA) have well-defined guidelines for the organization of data and open source software development[3]. Data releases throughout the field of astronomy more generally do not follow consistent patterns in terms of how the data can

[3] See NAS report http://sites.nationalacademies.org/SSB/CompletedProjects/SSB_178892

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. As more and more research requires access to datasets developed by missions and experiments funded by multiple agencies, inter-agency collaboration to ensure interoperability of datasets will become essential.

Recommendation: All current and planned surveys supported by NSF, NASA and DOE/Cosmic Frontier 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 endeavor to use open source code to create the data products in order that the community can learn how those data products were created. We are aware that support for continued use of the source code is a much larger endeavor, and the additional benefit of such support is not clear at this time. Agencies should include in survey budgets funding to enable adequate public access to the data, software, and data products of these surveys.

Recommendation: The three agencies should coordinate on the guidelines and expectations for the public 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 issue of public release of data sets, data products, data access tools, and related software is a complicated and rapidly evolving one. A review and update of the the AAAC Principles of Access is warranted.

Ensuring Long-term archiving and preservation of critical data: With the completion of a number of large-scale astronomical experiments (e.g. DES, PanSTARRS, and SDSS IV) and the construction of a new generation of surveys (e.g. the LSST, VLASS, SDSS V) the astronomical community will have access to a wealth of data covering many decades of the electromagnetic spectrum. The potential for scientific discovery using these surveys extends well beyond the lifetime of an individual program, often lasting several decades with discoveries that were never imagined in the original design of the program. Funding for the archiving and distribution of the data that these experiments generate is, however, often limited to the lifetime of the program itself, or a small number of years beyond the completion of observations. Many of the programs supported by the MREFC and MSIP programs generate data sets with potential for long-term impact but do not have data preservation plans or resources to support access to their data beyond the completion of the survey. This represents a risk in terms of the investments that have been made to create these experiments.

Finding: The agencies have made multi-billion dollar investments in astronomical telescopes, satellites, and experiments over the last decade. These world class facilities

will impact our understanding of the universe for decades to come, providing a resource for many generations of scientists. The scientific value of the data these observatories will generate often exceeds the lifetime of the mission itself. While NASA has a history of preserving data well beyond the lifetime of the mission, NSF/AST does not have a policy for investing in long-term data curation. The AAAC recognizes the need to preserve and serve astronomical data sets well beyond the lifetime of a mission or program.

Recommendation: The AAAC recommends that NSF develop a policy to support the archiving and distribution of data sets generated by large and mid-scale observatories beyond the lifetime of the individual experiments. Ideally, this policy would include interoperability with existing archives. This policy will principally apply to the data products from public surveys and will require the periodic evaluation of the value of extant data sets, to ensure that resources are efficiently allocated.

In addition to preserving existing datasets, it is important for the agencies to be able to take advantage of opportunities to greatly enhance the scientific payoff of experiments enabled by joint analyses of the data. An example of this is the possibility of enhanced scientific return represented by joint processing of LSST, Euclid and WFIRST.

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 teleconferences 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. The AAAC noted in our previous 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. We continue to do so now.

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 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, WFIRST, 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 continue to conduct useful investigations to explore coordination between science teams planning to use LSST, WFIRST, and Euclid to further the study of dark energy.**

Recommendation: We continue to 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.

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 interests. The rapidly growing prevalence of moving emitters, including cell phones, mobile wireless hotspots, car radars, and the proliferation of commercial micro- and nano-satellites, compounds the problem of protecting astronomical observatories from contaminating emission. This is especially true because the 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. As astronomical research has evolved, access to spectral regions beyond the protected "oases" has become critical (for example access to redshifted HI emission has become crucial for galaxy evolution and cosmology).
The impact of optical light pollution has been known and characterized for decades. Traditionally, control over light pollution has been exercised locally, 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 more strongly scattered by the atmosphere. This has led to an increase in the rate of optical light pollution that is increasing faster than the increase in ground illumination from artificial lights themselves.

The situation for the radio/sub-mm end of the spectrum is more clear, as jurisdiction over this portion of the electromagnetic spectrum is regulated by governmental and international agencies. Access to these frequencies is regulated by the FCC (for non-government entities domestically), NTIA (government organizations), and the International Telecommunications Union (internationally). Unfortunately, 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. At present, the NSF represents the astronomical community's interests by sending representatives to NTIA and 10 of its subcommittees, and by representing the NSF as part of delegations to CITEL (for western-hemisphere spectrum management coordination) and the ITU. Although the representation allows astronomers a voice at the table, the limited resources (both financial and personnel) available for spectrum protection and the increasing influence of other interests have over the years eroded the capability of astronomers to access uncontaminated portions of the spectrum.

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, and is at risk due to the competition for bandwidth. For example, JWST has been pushed to use the Ka band link due to saturation of the X band.

Finding: Competing interests continue to provide a severe and unrelenting threat to astronomers' ability to detect electromagnetic signals from space. Without clean access to these wavelengths, the ability of astronomers to obtain fundamental knowledge about the universe is profoundly impaired. This is particularly important as time-variable astronomy gains visibility (for example in detecting gravitational wave counterparts or other multi-messenger astronomy activities). Mobile and transient noise sources form a large and growing threat.

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: Given their common interests in access to the spectrum, 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. Efforts to engage and coordinate with other international agencies should continue.

4. Implementation of Decadal Survey Recommendations

4.1 Priorities Addressed or Under Implementation

4.1.1 Space-based Projects

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

The *Wide-Field Infrared Survey Telescope* (*WFIRST*):
WFIRST 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. 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.

In 2018, WFIRST passed its System Requirements and Mission Design Reviews, and was approved to enter Phase B (preliminary design). The primary mission elements completed their system design reviews and all major contracts were awarded. In the current year, flight hardware is in production, and the mission is on track towards the Preliminary Design Review, with a target launch date of 2025.

Finding: NASA's Wide Field Infrared Survey Telescope (WFIRST) as approved to enter phase B would deliver the science identified for the version of WFIRST recommended in NWNH and provide an important technology demonstrator for future coronagraphic missions.

Recommendation: The AAAC continues to recommend ongoing cost assessment and mission review of the Wide Field Infrared Survey Telescope (WFIRST) prior to and after Preliminary Design Review.

The President's requested budget for FY 2020 does not include funding for WFIRST.
As noted in previous annual reports, particularly in the 2017-2018 report where we addressed the issue of WFIRST cancellation in the FY 2019 budget request (a cancellation not supported by the continued appropriation of funds to WFIRST by Congress), the AAAC supports balanced investments (e.g. of science and facilities on a variety of scales) 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.

Finding: The President's requested level of FY 2020 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 2020 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 President's 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*. The LISA Preparatory Science (LPS) program Announcement of Opportunity appeared in early 2018 as an element of the 2018 ROSES call, with a proposal deadline in June of 2018. Nine proposals were selected in December 2018 for funding. Together with a growing pulsar timing array (PTA) the development of LISA will expand gravitational wave astrophysics to black hole mergers on all mass scales (stellar to super-massive systems residing at the centers of essentially all galaxies. These studies will address fundamental questions associated with the growth of black holes on cosmic time scales.

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

Explorers Program Augmentation: This NASA program of relatively low-cost missions, quickly deployed, has a history of high scientific impact, including both the Uhuru and Cosmic Background Explorer (COBE) missions leading to Nobel prizes for their investigators. A high priority of *NWNH* was a significant expansion of the existing NASA Explorer program, including

at least four Explorer Announcements of Opportunity during this decade, each with Mission of Opportunity calls and mission selection. *NWNH-AMA* reiterated that NASA should preserve this goal to provide opportunities for the rapid realization of new scientific opportunities in space.

The 2011 Explorers call led to the selection of TESS, an all-sky search for transiting extrasolar planets as a MIDEX mission, and NICER, a Mission of Opportunity X-ray observatory attached to the International Space Station to study the interior composition of neutron stars. (Both TESS and NICER are described in additional detail, below.) A second 2014 call selected IXPE (Imaging X-ray Polarimetry Explorer) as a small explorer (SMEX) mission, which is slated for launch in 2020, and the Mission of Opportunity GUSTO, an Antarctic balloon mission to study the ISM at terahertz frequencies. The third Explorers call in 2016 recently led to the selection of SPHEREx in February 2019. SPHEREx is an all-sky optical and near-IR survey mission. One additional Partner Mission of Opportunity is still under consideration at this time. The fourth Explorers call of the decade was released on April 1, 2019 soliciting small explorer (SMEX class) missions and Missions of Opportunity. Assuming this fourth call proceeds to mission selection as planned, the *NWNH* recommendation for expansion of the Explorers program in the current decade will be fulfilled.

Finding: The AAAC commends the NASA Astrophysics Division on fulfilling the recommendation of *NWNH* and *NWNH-AMA* that at least four Announcements of Opportunity for the Explorer program be executed this decade. The Explorer program has provided and continues to provide a valuable complement of agile, low-cost missions in space to the NASA portfolio.

***CubeSat Initiative*:** Beginning in 2017, NASA Astrophysics Division R&A contained budget allocations for CubeSat development. Related to the CubeSat Initiative, in February 2018 a call for astrophysics SmallSat studies was released. From this program, 9 proposals were selected for 6-month concept studies, covering a broad range of astrophysical disciplines. The SmallSats program includes CubeSats, CubeSat constellations, and other standard-form payloads.

Finding: The AAAC supports the NASA Astrophysics Division CubeSat initiative and NASA's expansion of SmallSat development.

***TESS*:** TESS is an all-sky survey to search for transiting exoplanets orbiting the brightest stars in the sky. The level-1 science requirement of the mission is to measure the masses of 50 planets smaller than 4 Earth radii. While TESS discovers candidate transiting exoplanets and measures their sizes, ground-based telescopes are required to follow up these candidates and to provide radial velocity measurements of their masses. One of the facilities that is expected to

be used to measure the masses of TESS-discovered planets is the NEID spectrograph, which is funded by the NN-EXPLORE partnership between NASA and NSF. TESS additionally supports a robust guest investigator program. The first call for guest investigator programs with TESS led to 31 selected investigations covering a broad range of astrophysical topics at the end of 2017. A second call had proposals due in mid-March of 2019.

The TESS mission was launched successfully on April 18, 2018. Following a commissioning stage, TESS began full science operations on July 25. TESS will complete its one-year survey of the southern hemisphere in mid-July of this year and will then execute a second full-year survey of the northern hemisphere sky. TESS is currently meeting or exceeding all of its performance expectations. As of February 2019, TESS was already well on its way toward completing its level-1 science requirements. Thirty small planets less than 4 Earth radii already had mass measurements underway, and an additional six such planets have completed mass measurements. The TESS satellite has sufficient fuel and orbital stability to continue on for an additional 2+ decades. An extended mission plan has recently been proposed as a part of NASA's Senior Review process.

Finding: NASA's TESS mission is performing at or beyond its expected level and is currently well on its way toward meeting its level-1 science requirements. The AAAC notes that the exoplanet mass measurements required to meet the TESS level-1 science requirements are only partly funded by NASA and NSF efforts, with the rest coming from private and/or international resources.

Multi-Messenger Astrophysics: The gravitational wave observation by LIGO of coalescing neutron stars followed by prompt detection of the source in multiple electromagnetic wavelength bands had significant contributions from currently operating space missions. In particular, the Fermi Gamma-ray observatory detected gamma rays from the merger nearly coincident in time with the LIGO detection. In conjunction with ground-based observations of the afterglow associated with GW170817, this led to the discovery of so-called kilonova emission and lend strong support for theories identifying such merger environments as a site for the synthesis of elements. It is currently believed that binary neutron star (BNS) mergers create the right conditions for the r-process (rapid capture of neutrons, in relation to beta decay time scales). This process is uniquely responsible for a significant number of isotopes beyond the so-called iron peak. The creation of neutron rich plasma in BNS mergers leads to characteristic emission following the merger (which creates a black hole) that ground based spectroscopic follow-up can record. The interpretation of the spectral evolution of this afterglow hinges on complex aspects of radiation transport in exotic matter, and has led to a significant effort in the area of Laboratory astrophysics. Measuring the properties of highly ionized isotopes in the neutron rich part of the nuclear chart is required to model kilonovae, and provides a key example in support of inter-agency collaborative approaches to ultimately unravel natures most violent phenomena.

Finding: The AAAC recognizes that NASA's space mission portfolio has great potential for supporting the emergent area of multi-messenger astrophysics that has been opened by the NSF supported observations of gravity waves. 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, as well as Laboratory Astrophysics.

The James Webb Space Telescope (JWST): JWST was the top space-based recommendation of the previous decadal survey, *Astronomy and Astrophysics in the New Millennium* (2001), and NASA subsequently committed to the project. The complexity and enormity of the effort meant that this responsibility continued into the *NWNH* decade, engendering constraints on NASA not fully accounted for at the time of the *NWNH* survey and its generation of a prioritized set of recommendations. JWST will be the most powerful telescope ever launched into space. Its four science instruments will operate in the near- and mid-infrared, where light is able to penetrate regions of gas and dust, enabling unique studies of highly redshifted stars and galaxies of the early Universe, and where the spectral signatures of molecules in exoplanet atmospheres are most prominent. Follow-up with JWST of high redshift gamma-ray bursts will enable the study of cosmic chemical evolution, tracing the abundance patterns in the first star forming regions of the universe.

In June of 2018, a launch delay of JWST was announced, following the discovery of a hardware issue involving loose fasteners on the telescope's sunshield. The hardware issue has since been rectified, and all necessary repairs have been made. The JWST mission is now re-baselined for a March 2021 launch, with plans proceeding on target with that goal. In 2018 the spacecraft and sunshield were integrated, and acoustic tests on the assembly were completed. Environmental testing on the spacecraft assembly is slated for completion in the summer of 2019, and at least one additional test deployment of the sunshield is planned.

Finding: JWST remains an essential component of the astrophysical science landscape. The observatory is currently on track for a 2021 launch.

Recommendation: NASA should continue to allocate resources to successfully launch JWST at the earliest possible date.

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 the ISS, 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. NASA-NSF-DOE are

jointly engaged in this research arena, and 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. The power of NICER is its high time resolution: single photon time-stamping with an accuracy of ~100 nsec in the 0.2-12keV X-ray regime. Its energy resolution is ~1.5% at 6 keV. Working towards its key objective, the neutron star dense matter equation of state, NICER quickly accumulated results on others sources as well, including black hole binaries, thermonuclear bursts, accreting millisecond pulsars, active stars and extragalactic sources. These results were presented in a 2018 Focus Issue of The Astrophysical Journal Letters. To name just one highlight, the discovery of weakening quasi-periodic oscillations in the X-ray emission of Aql X-1 enabled their interpretation as accretion rate variations at the inner edge of the accretion disk, as opposed to being caused by spin-induced strong gravity effects. 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.

***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. The most recent next generation SOFIA instrument solicitation was released in early 2018 with a due date of August, 1 2018.

Jointly funded by NASA and the German Aerospace Center, SOFIA's initially agreed upon 5-year prime mission will be completed at the end of FY19. At the end of a prime mission, NASA usually assesses the science performance, management of a program, and proposed future science to decide on an extension of the program through a Senior Review Process, as required by the 2005 NASA Authorization Act. The 2018 Consolidated Appropriations Act, however, redefined the prime mission length, and explicitly dismissed SOFIA from the 2019 Senior Review. In the absence of a Senior Review, SOFIA is undergoing science and operations reviews in late 2018 and early 2019, respectively. These reviews do not consider closeout or cancelation of the SOFIA mission.

Recommendation: The AAAC recommends to Congress that SOFIA's prime mission be considered complete at the end of FY2019, and that SOFIA undergo senior review in the next regular review cycle, in line with normal NASA review procedures.

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 the highest priority for the DOE-HEP Cosmic Frontier in the 2014 P5 strategic plan, this project moved into the construction phase and the camera received DOE Critical Decision 3 (CD-3), start of full construction, in August 2015. The NSF-funded part of the project is now significantly advanced and the DOE-funded LSST camera has completed funding in FY 2018. 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). NSF/AST stated that the NSF share of the operations funding does represent a significant of the annual expenditures of the divisions and a continued flat-funding profile would require a major revision of the planned facility support operations in order preserve a balance 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 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)*:* In response to the NWNH recommendation the NSF/AST established the Mid-Scale Innovations Program (MSIP) in 2014 to fund medium scale projects which are too small to be funded by the Major Research Equipment and Facilities

(MREFC) line but too large for individual grants. The program is run biennially with calls in FY14, FY16, and FY18. A solicitation is expected in the summer of 2019 with funding for FY20. The program budget is in the $15-20M range with proposals in the cost range of $4-30M. Funding levels lower than $4M were considered for proposals to provide open or community access to a facility or survey dataset. 23 awards have been made to date with budgets of $600K to $10M (15 standalone programs and 8 access awards). 21 of these awards are still active. Funding for the MSIP program remains below that envisaged by the NWNH

Finding: The AAAC appreciates and supports the work by NSF/AST to develop and sustain the Mid-Scale Innovations Program (MSIP). The projects supported by this program are beginning to produce exciting scientific returns for the astrophysics community.

Recommendation: NSF/AST should continue to grow and develop the MSIP program in the context of a balanced portfolio. Care should taken to evaluate the progress and management of these programs after the award and to ensure that the promises for community access to the facilities and data are realized. NSF/AST should review the impact of community access to MSIP funded programs periodically throughout the life of the award.

Mid-Scale Research Infrastructure (MSRI)*:* As part of NSF's 10 big ideas it has implemented the Mid-Scale Research Infrastructure program (MSRI). This NSF-wide program was to enable the development and upgrade of research infrastructure that will support clearly identified needs within the science and engineering communities. MSRI is open to Federally Funded Research and Design Centers including NSF/AST observatories. MSRI was offered for the first time in FY19 with two programs. MSRI-1 was to support design ($600K to $20M) and implementation ($6M to $20M) proposals. 246 preliminary proposals were received with full proposals (from those invited to apply) due in May 2019. Preliminary proposals for MSRI-2 (infrastructure only) were due March 11th 2019, with nearly 100 letters of intent submitted. The sum total of funding requested from the MSRI-1 and 2 programs exceeded $4 billion, indicating a significant unmet need in the NSF community.

Finding: The AAAC is pleased to see the development of the Mid-Scale Research Infrastructure program (MSRI). The very large number of proposals that were submitted in response to the initial call demonstrates the significant need within the science and engineering community for renewed infrastructure to support ongoing and future science programs.

Recommendation: NSF/AST should ensure that the astronomical community is aware of the MSRI opportunities and in particular the range of infrastructure projects that can be supported by this program.

The Dark Energy Spectroscopic Instrument (DESI): DESI is a DOE HEP-led project with contributions from NSF/AST, universities, private foundations and international agencies that is currently under construction, and will start operations in FY20. In 2014, P5 encouraged DOE-HEP to support DESI as part of its broad-based dark energy program. DOE is providing a new, next-generation spectrograph and related instrumentation and computing systems. DOE/HEP and NSF/AST 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 the installation of the spectrograph on the Mayall telescope. DESI achieved CD-3 by DOE in June 2016. Installation started in 2018 onto the Mayall 4-m telescope at Kitt Peak National Observatory in Arizona, operated by AURA/NOAO on behalf of the NSF. The top end of the telescope started to be converted in February 2018 and the first spectrograph was installed on the rack at the Mayall Telescope at the beginning of 2019. Of the ten spectrographs that are part of DESI, three have been shipped to the observatory and a further two are undergoing tests. 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. A review of Project status was conducted in November 2018. The primary imaging survey for DESI, DECaLS (DECam Legacy Survey), covering 2/3 of the DESI survey footprint, the MzLS northern imaging survey (using the Mayall 4m in the z-band), and the BASS imaging survey (using the University of Arizona's Bok 2.3m telescope) have all completed observations. Processing of these data is ongoing and the upcoming data release, DR8, will be the first data release that combines data from all 3 surveys across the sky.

Daniel K. Inouye Solar Telescope (DKIST)**:** DKIST is a 4m aperture, off-axis, telescope under construction at the Haleakalā Observatory in Maui (Hawaii). The off-axis design allows observations of the off-limb solar corona and measurements of the coronal magnetic field. DKIST started the Integration, Testing and Commissioning (IT&C) phase in 2018. This last phase of the construction is expected to end in June 2020. The primary mirror and the secondary mirror of the telescope have already been integrated. As part of the IT&C phase, the first images of the Sun are planned for late summer 2019.

Laser Interferometer Gravitational-Wave Observatory (LIGO): Advanced LIGO, the ground-based gravitational wave experiment, started 02 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. On August 17, 2017, LIGO observed the gravitational wave signature of two merging neutron stars. These observations initiated the new window of multi-messenger astrophysics, and in the case of the first binary neutron star merger the only missing signature was in the neutrino-sector. Advanced LIGO completed the O2 run in August 2017. Upgrades for the third observing run, O3, were completed in September 2018, and after commissioning and engineering runs O3 began in April, 2019. The first public alert from O3 (a binary black-hole merger at a distance of ~1473 Mpc) was announced on April the 8th. Advanced LIGO and VIRGO will be run in unison for O3.

Data from O2 together with open source tools software for analyzing these data were released by the LIGO consortium. LIGO was awarded a $35M grant to upgrade the system as part of Advance LIGO Plus.

Dark Energy Survey (DES): DES 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. It was recommended as a DOE priority in the 2007 P5 report. The 520 megapixel Dark Energy Camera (DECam) was funded by the U.S. Department of Energy Office of Science and is mounted on the Blanco 4-meter telescope at CTIO, which is operated by NOAO (NSF). In January 2019, DES completed its data collection after 758 nights of observations (commencing in August 2013). In total, DES collected ~50 terabytes of imaging data covering 5,000 square degrees. DES has released cosmological measurements and constraints from the year-1 data and the first cosmological constraints from a subset of the first three years of type Ia supernovae observations. In January 2018, DES made publicly available the first 3 years of survey data as part of its DR1 data release.

Finding: The AAAC Commends the DES team, DOE, and NSF for successfully completing DES operations and for transferring DECam to become a community instrument

Dark Matter: Understanding and identifying the nature of dark matter is a priority of both P5 and *NWNH* reports and both laboratory and astrophysics experiments/investigations will be needed. *NWNH* identified understanding the nature of dark matter as a science frontier question for advancing knowledge, underscoring the need for both direct detection and indirect detection. P5 stressed the complementary approach combining direct detection of dark matter, indirect detection, and accelerator searches. Three G2 direct detection dark matter experiments were selected for development in June 2014 by DOE/HEP and NSF/PHY. Two experiments, Super Cryogenic Dark Matter Search at Sudbury Neutrino Observatory Lab (SuperCDMS-SNOLAB) and LUX-Zeplin (LZ) search for weakly interacting massive particles (WIMPs), and the Axion Dark Matter eXperiment Generation 2 (ADMX-G2) is sensitive to axions. FY19 marks the completion of funding for the LZ and SuperCDMS construction projects. DOE HEP and NSF/PHY are supporting operations of SuperCDMS-SNOLAB and DOE HEP will support LZ operations. ADMX-G2 started operations in its first frequency range in January 2017 and reached a key sensitivity threshold in August 2017 and is currently in its 3rd successful phase of data taking.

While the search for WIMPs continues, the community has begun to explore alternative dark matter candidates. The community has led this effort and the funding agencies are responding to the scientific push into these new areas of research.

Finding: Alternatives to the standard (WIMP) dark matter scenario can be explored in a wide variety of ways, and the community is devoting time and resources to develop new

search techniques. DOE-HEP set up a Basic Research Needs group to assess the landscape. There are potential synergies with exciting developments in the area of quantum sensors.

Recommendation: DOE-HEP should continue to pursue searches for alternatives to the standard dark matter candidates.

Cosmic Microwave Background: All three agencies are now fully supporting CMB Science. While waiting for the outcome of the next Decadal Survey to help guide the construction of the expected large surveys in the 2020's, the community has come together to construct and operate exciting Stage-3 surveys, such as the South Pole Telescope, Atacama Cosmology Telescope, and BICEP/Keck among others. These experiments contain information that correlates with that obtained from galaxy surveys, so cross-correlations between these two very different sets of experiments has emerged as an exciting field and yet another reason to continue this research. The community has also come together in support of CMB-S4, a proposed ground-based experiment that is the sole project recommended by the 2014 P5 Committee that is not yet under construction. The science case for all of these projects is well developed.

Atacama Large Millimeter/submillimeter Array (ALMA): The world was captivated on April 10, 2019 when the Event Horizon Telescope (EHT) announced that it had produced the first image of a black hole. As the most sensitive and largest element of the EHT, ALMA was instrumental in making this observation possible. With ALMA, the EHT achieved one of the highest resolutions ever in astronomy, 20 microarcseconds. A microarcsecond is about the size of the period at the end of this sentence if you were observing it from the Moon.

The extraordinary science from ALMA emerged from decades of planning. ALMA 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. *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*[4] (A. E. Whitford, 1964) and recommended by the following decadal survey report, the 1972 *Astronomy and Astrophysics in the 1970s*,[5] the *VLA* has enabled transformational science as a premiere radio telescope at centimeter wavelengths. Its combination of sensitivity and high angular resolution allow it to match the imaging capability of ground-based OIR telescopes. An upgrade of the *VLA* was recommended

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

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

by the 2001 decadal survey report *Astronomy and Astrophysics in the New Millennium,*[6] 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. The VLA Sky Survey (VLASS) a sky survey covering 2-4 Ghz at 2.5 arcsec resolution has started the second half of the first epoch survey. These observations, expected to be finished in July 2019 will complete coverage of the sky above declination -40 deg.

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

In 2016, the mid-decadal review conducted by the National Academies revisited the progress of the NSF toward achieving balance in its portfolio while dealing with the challenge of growing operations costs of facilities. As noted in *NWNH-AMA*, “The committee strongly supports the goal of a balanced program that includes facilities, mid-scale initiatives, and small-scale initiatives. Maintaining this balance is a challenge at the current level of funding.” This is

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

particularly the case when LSST and DKIST operations begin. As a result, carrying out the recommendations of the 2012 Portfolio Review Committee (PRC) report for facility divestment continues to be a priority. Otherwise the recommended balance in supporting individual investigator grants, mid-scale initiatives, and facility operations will not be achievable.

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 continues to agree with this motivation and concern.

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

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 an updated 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 2016-2020. Recently they were approved for a two year extension of operations.

● Mayall 4m: The DESI survey will use this telescope along with newly supplied multi-fiber Spectrographs under an MOU between NSF and DOE.

● WIYN 3.5m: An 2015 MOA between NASA and NSF 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).

● Green Bank Observatory: The Final Environmental Impact Statement (EIS) is currently pending NSB approval. Separation from NRAO occurred in 2017. An MOA is in work for a new partner, but more partners are desired.

● Long Baseline Observatory / Very Long Baseline Array (VLBA): There was a separation from NRAO, but not AUI, in October 2016. An MOA is in place with the US Navy to share 50% of the operating cost of VLBA.

● McMath-Pierce Telescope: A grant from the National Science Foundation (NSF) has been awarded to the Association of Universities for Research in Astronomy (AURA) for the development of a new “Windows on the Universe Center for Astronomy Outreach” at NSF’s Kitt Peak National Observatory.

● GONG/SOLIS: SOLIS has moved to Big Bear. NOAA/SWPC covers GONG operations cost.

● Sacramento Peak Telescope: The Sac Peak EIS has finalized and recommends partial operations of the facility with NSO operating site facilities and the NMSU-led consortium in charge of the scientific planning of the Dunn Solar Telescope (DST) and the Visitor's Center.

● Arecibo: Management has changed in 2018 to a consortium led by the University of Central Florida with its partners, Universidad Metropolitana in San Juan and Yang Enterprises, Inc. in Oviedo. Funding is being deployed to provide repairs following the 2017 hurricane Maria event.

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

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 to produce excellent science while reducing or eliminating the cost to NSF of operating these facilities.

Recommendation: The AAAC recommendations that the NSF facility divestment process be completed 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.

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 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.* These projects are the Giant Magellan Telescope (GMT), to be sited in Chile, and the Thirty Meter Telescope (TMT), to be sited in Hawaii. At the January 2019 meeting of the AAS, a presentation was made advocating for a US-ELT program. This program, supported by key science programs developed by members of the community in late 2018, proposes to obtain 25% or more of the time on both the GMT and TMT to provide the community access to these facilities and cover both hemispheres of sky. While an exact cost for the program was not given, it is anticipated to be of a similar scale of investment to other facilities like ALMA and LIGO (~$1billion or greater). It is likely that the upcoming Decadal Survey will have to re-assess the GSMT recommendation in the light of the US-ELT proposal.

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 stated in previous reports, 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.

The new National Center for Optical Infrared Astronomy (NCOA) represents a merger of Gemini, NOAO, and LSST into a single matrixed organization. The principal components of NCOA comprise a Community Science and Data Center (CSDC), the Mid-Scale Observatories (the NOAO 4m telescopes), Gemini, and LSST. A proposal for the operation of NCOA has been submitted to the NSF by AURA and the position of NCOA director has been advertised. It is expected that NCOA will begin as an organization in October 2019 pending approval by the NSF. NCOA will be responsible for the implementation of the OIR System Report recommendations

Recommendation: Efforts by AURA, and 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 (range of program scales and investment 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 cessation of WFIRST (top-ranked space-based priority from *NWNH*) in FY 2020 would be a striking exception to the way that the federal government previously followed the priorities recommended by the community through the decadal survey process.

5. GBS report

The NSF operates or shares multiple medium-large (4-8m) optical telescope facilities that currently form the backbone of the US optical/near-infrared system. In 2015, the NRC issued a report that recommended that these facilities be optimized to maximize the scientific return in the era of the new and imminent facilities such as LSST and ALMA.
Although long term priorities for federally funded facilities necessarily will depend on the outcome of the 2020 decadal survey, the evolution of scientific landscape in the past few year (for example the emergence of multi-messenger astronomy, developments in adaptive optics, the development of DOE-supported dark energy experiments, and the increasing importance of time domain astronomy) have changed the priorities of the facilities. Furthermore, NSF will be required to make programmatic decisions in advance of the decadal survey report (expressions of interest in the Gemini telescope were needed by November 2018, and both the Gemini and SOAR partnership agreements will need to be renegotiated before the 2020 Decadal results are known.

As a result, in August, 2018, the AAAC in coordination with NSF/AST and DOE/HEP appointed a subcommittee to investigate the role of the Gemini, Blanco, and Soar (GBS) telescopes in the first part of the next decade. The committee, chaired by Klaus Honscheid (Ohio State), was charged with: 1) assessing to which degree each of the telescopes provides critical complementary data for LSST, MMA, time domain and dark energy science; 2) describing and evaluating highest impact science in other areas given the planned suite of instruments of these facilities; 3) assessing whether the current US share in Gemini and SOAR is adequate; 4) evaluating modes of multi-facility use to maximize the scientific output of the GBS as a system; and 5) highlighting missing instrumental and adaptive optics capabilities needed for the highest priority programs.

The committee consisted of 9 researchers spanning most of the areas of astronomical research. The committee reviewed the successful proposals to the telescopes, publications resulting from the telescopes,and had access to programmatic studies from the facilities. In addition to weekly teleconferences, the committee met face-to-face in October, 2018 in Tucson. At that meeting,

the committee received presentations from the directors of the GBS facilities and consulted with experts in some areas where the committee expertise was thinnest.

The committee presented a preliminary set of findings to the AAAC and NSF in November, 2018 (to help inform the Gemini expression of interest), and a preliminary version of the report was given to AAAC in January, 2019. The final report was accepted by AAAC on March 8, 2019. The report of the GBS subcommittee is attached as an appendix. Here we summarize the conclusions of the report.

Overall, the GBS subcommittee found that the scientific potential of all three (G,B, and S) was strong, and that the existing and planned instrumentation will support transient science (especially Gemini-South with the new SCORPIO instrument). At the same time, better integration of the telescopes to optimize for follow-up observations is called for. More generally, the subcommittee recommends that the NSF coordinate the development of open-source tools (such as event brokers, and TOMS) to allow for efficient transitions from alerts from LSST to observations by GBS facilities. On the GBS ends, enabling queue mode capabilities on Blanco and SOAR will increase their capability for time domain and multi-messenger observations.

On the instrumentation front, the GBS committee recommends that support continue for the instrumentation in development (such as SCORPIO) and planned instrumentation (such as the Gemini-North AO upgrades). However, the committee also recommended attention be paid to development of instrumentation to cover capabilities missing (such as a fast low-dispersion spectrograph for SOAR, or instrumentation for the Blanco for the mid-2020s. Finally, the committee also recognized the lack of an adequate multiplexed wide-field spectrograph to match to LSST.

Finding: the AAAC finds that the GBS subcommittee report addresses the charge questions and provides an evaluation of the important role of the GBS telescopes in the US system in the first part of the next decade.

Recommendation: the NSF should work towards implementing the recommendations of the GBS subcommittee, particularly those that affect the impact of the GBS system over the next ~5 years, before the Decadal Survey recommendations take precedence.

6. Preparation for 2020 Decadal Survey

6.1 General preparation informed by past experience

Planning is well underway for the 2020 Decadal Survey of Astronomy and Astrophysics (DSAA). The Co-Chairs of the Survey, Drs. Fiona Harrison and Robert Kennicutt have been chosen, and

the Steering Committee selection process is underway. The value of this community-based effort is 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 also 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 remain now, for the 2020 Decadal Survey, and beyond:

- *NWNH-AMA* recommends that independent cost estimates for projects be retained
- *NWNH-AMA* recommends that more extensive funding partnerships outside the agencies be developed. The recent NASA/ESA/JAXA collaborations on Athena, Euclid, LISA, and XRISM (formerly 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).

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.

Finding: The agencies have responded appropriately to the NWNH-AMA recommendations regarding independent cost assessment.

Finding: Recent collaborations between NASA and international partners on Athena, Euclid, XRISM, and LISA further the recommendations of NWNH and NWNH-AMA.

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.

Recommendation: The AAAC recommends that the next Decadal Survey continue to obtain input from the community through white papers and direct engagement. The AAAC further recommend that the Decadal Survey make every attempt to engage all members of the astronomical community (including industrial partners, international partners, and philanthropic organizations) and pay particular attention to obtaining input and panel membership from as diverse a spectrum of the community as possible.

6.2 Upcoming Mission Concept Development

Future NASA Mission Concepts: In 2015, NASA commissioned the Enduring Quests and Daring Visions study[7]. 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); two UV/Optical/Near Infrared telescopes (HabEx and LUVOIR); and an X-ray telescope (Lynx). The results of these extensive studies will flow into the next Decadal Survey, as will those studies aimed at Probe Class missions addressing the many exciting questions including those of modern time domain astronomy (the physics of transients) and the recently opened window of Multi-Messenger Astrophysics (light, gravitational waves and neutrinos). In addition, the latter field received a tremendous boost from the discovery of several black hole binary mergers and the first neutron star binary merger (GW170817/GRB170817A) which engaged LIGO/Virgo as well as space-based observatories (Fermi/GBM, Swift, INTEGRAL) and a global network of ground-based observatories operating across the electromagnetic spectrum.

The 2020 Decadal Survey will likely recognize the breakthroughs in time domain astrophysics, multi-messenger astrophysics, and the expanding field of exoplanet research and should inform the agencies on how to optimize their portfolios to incorporate these new frontier areas of research.

Future Ground Based Concepts:
In 2016, the NSF introduced a set of Big Ideas[8], aimed at long-term development of visionary

[7] http://go.nasa.gov/1gGVkZY
[8] https://www.nsf.gov/news/special_reports/big_ideas/

frontier directions in science and engineering. Of highest relevance to astrophysics in this context is the “Windows on the Universe” segment, within which the era of multi-messenger astrophysics is emphasized. 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 WWII 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.

In addition to the US-ELT program mentioned previously in this report, three other large ground based concepts were presented to the AAAC in the February 2019 meeting. The *Next Generation VLA* (ngVLA) proposes a suite of arrays (a Main array of 214 antennas, a Short Baseline array of 19 antennas, and a Long Baseline array of 30 antennas) to significantly improve over the current VLA facility and address an extremely wide range of science goals, including multi-messenger astronomy. ngVLA is anticipated to require a U.S. contribution of $1.75 billion for construction and $80 million/yr in operations (2018 dollars). The *Ice-Cube-Generation 2* is a proposal to significantly expand the Ice Cube neutrino detection experiment, increasing the sensitivity over the Ice Cube 7-year value by a factor of 10. The new array would be comprised of 120 strings of sensors, with a volume 10 times that of the original Ice Cube experiment. The notional fiscal scope for the array is on the order of $300 million. Finally, the *Cosmic Microwave Background Stage 4 (CMB-S4)* project was presented. A detailed description of CMB-S4 resulted from a subcommittee report delivered to the AAAC in 2017. The notional construction costs are $412 million, and operations and science costs are $32 million per year.

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 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 agencies and the community for their commitment to these principles.

Finding: We find that the Decadal Survey process is important for ensuring that the US remains a global leader in scientific exploration and technology development.

7. Budget Summary and Impact

FY 2018 & 2019 Budget Status:
Both the FY 2018 and FY 2019 budget cycles were significantly delayed. These delays, particularly the protracted period of partial government shutdown, caused both tangible and intangible negative effects across the agencies. Although evidence is currently only anecdotal, there is concern that the recent shutdown has led to an increase in personnel departures from the agencies. Furthermore, delays in appropriations lead to delays in implementation of *NWNH* recommendations, agency science priorities, and day-to-day operations of facilities and grants management. For NSF, a major challenge from the shutdown was maintaining funding flow to facilities awardees, especially those with Chilean labor contracts. All together, delays and shutdowns created risks to the management of programs, missions, facilities, and grant awarding.

Nevertheless, once completed, the FY 2018 and FY 2019 budgets represented a net positive for funding of astronomy and astrophysics at the agencies. Of note, Congress opted not to cancel WFIRST as requested by the Administration for FY 2019. Also of note, NSF AST was able to fund the MSIP program at levels commensurate with those envisioned by *NWNH* along with funding other programs and forward-funding some operations of DKIST and LSST operations with the increases in FY2018 funds. The impact of FY2019 increases on AST are yet to be assessed by the committee.

Finding: The funding levels appropriated by Congress in the FY 2018 and FY 2019 budgets generally positively impacted all three agencies' ability to meet the recommendations of *NWNH*

Finding: Delays in passing the appropriations for the agencies for FY 2019 create challenges and added risks for the efficient management of programs, missions, facilities, and the award of research grants.

Finding: Protracted periods of government shutdown have significant negative impact on the short-term ability for the agencies to manage programs and portfolios. Additionally, they create additional risk for personnel loss at the agencies, creating further strain on the agencies' ability to perform their missions.

FY 2020 Budget Concerns:
Although the Administration's FY 2020 budget request has only just been released and reviewed by the committee, even a cursory examination causes significant concern. The budget for NASA would again call for the cancelation of the WFIRST mission, the highest space mission priority of *NWNH*. A WFIRST cancellation would be a substantial departure from the vision of *NWNH* and would likely jeopardize future missions of similar or larger scale that might be recommended in the 2020 Decadal Survey.

Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for NASA above the Administration's request to continue to provide a balanced program within astrophysics in line with the recommendations of *NWNH*.

The Administration's FY 2020 budget request contains significant cuts to both facility and research budgets at NSF, both on the order of 30% relative to the FY 2018 enacted values. These cuts not only jeopardize the NSF's current ability to balance the need for world-class facilities and the community of researchers that use them, but also significantly threatens this balance in future years as facilities like LSST come on line. NSF will not be able to meet the priorities outlined in *NWNH* if the FY 2020 budget request is enacted.

Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for NSF above the Administration's request to enable the Agency to properly balance research and infrastructure funding needs to meet the recommendations of *NWNH*.

The FY 2020 budget request also proposes significant cuts to the DOE High Energy Physics Program relative to the enacted FY 2019 amounts. The request is below the lower boundary identified by the P5 report in its budget scenarios, and will create challenges for the ability of the DOE to fund extramural grants and maintain future progress.

Recommendation: The AAAC urges Congress to increase the proposed FY 2020 appropriation for DOE High Energy Physics above the Administration's request to provide adequate funding for operations of and research and analysis of data from the numerous world-class facilities currently nearing completion.

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, 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 Abbreviations

AAAC	Astronomy and Astrophysics Advisory Committee
AAG	Astronomy and Astrophysics Grant
AAS	American Astronomical Society
ACTA (or CTA)	Atmospheric Čerenkov Telescope Array
ALMA	Atacama Large Millimeter/submillimeter Array
ATI	Advanced Technologies and Instrumentation
AUI	Associated Universities, Inc.
AURA	Association of Universities for Research in Astronomy, Inc.
ADMX	Axion Dark Matter eXperiment
CAA	Committee on Astronomy and Astrophysics
CD	Critical Design review
CDT	Concept Definition Task Force
CMB	Cosmic Microwave Background Radiation
CTA (or ACTA)	Atmospheric Čerenkov Telescope Array
DECam	Dark Energy Camera
DES	Dark Energy Survey
DESI	Dark Energy Spectroscopic Instrument
DKIST	Daniel K. Inouye Solar Telescope
DOE	Department of Energy
DOE/CF	Department of Energy High Energy Physics Cosmic Frontier
EIS	Environmental Impact Statement
EMS	Electro Magnetic Spectrum
ESA	European Space Agency
ESO	European Southern Observatory
FACA	Federal Advisory Committee Act

FDR	Final Design Review
FY	Fiscal Year
GEO/AGS	Geosciences Directorate/Division of Atmospheric and Geospace Sciences
GONG	Global Oscillation Network Group
GSMT	Giant Segmented Mirror Telescope
HCT	Himalayan Chandra Telescope
HEP	High Energy Physics
HEPAP	High Energy Physics Advisory Panel
HST	Hubble Space Telescope
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JWST	James Webb Space Telescope
KPNO	Kitt Peak National Observatory
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
LSST	Large Synoptic Survey Telescope
LZ	LUX-Zeplin
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MPS	Mathematical & Physical Sciences (NSF Directorate for …)
MREFC	Major Research Equipment and Facilities
MRI	Major Research Instrumentation
MSIP	Mid-Scale Innovation Program
NAOJ	National Astronomy Observatory of Japan
NASA	National Aeronautics and Space Administration
NASA/APD	National Aeronautics and Space Administration Astrophysics Division
NEID	NN-explore Exoplanet Investigations with Doppler spectroscopy
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NSB	National Science Board
NRC	National Research Council
NSF	National Science Foundation
NSF/AST	National Science Foundation Division of Astronomical Sciences
NSF/OPP	National Science Foundation Office of Polar Programs
NSF/PHY	National Science Foundation Division of Physics
NuSTAR	Nuclear Spectroscopic Telescope Array
NWNH	The 2010 NRC decadal survey report "*New Worlds, New Horizons in Astronomy and Astrophysics*"
NWNH-AMA	The 2016 NRC mid term assessment report, "*New Worlds, New Horizons in Astronomy and Astrophysics, A Midterm Assessment"*
OIR	Optical InfRared

OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
P5	Particle Physics Project Prioritization Panel
PRC	National Science Foundation Portfolio Review Committee
R&D	Research and Development
SDSS	Sloan Digital Sky Survey
SMD	Science Mission Directorate, NASA
SOAR	SOuthern Astrophysical Research Telescope
SOFIA	Stratospheric Observatory for Infrared Astronomy
SOLIS	Synoptic Optical Long-term Investigations of the Sun
SPT	South Pole Telescope
STEM	Science, Technology, Engineering and Math
Super CDMS	Super Cryogenic Dark Matter Search
TAG	Tri-Agency Group
TESS	Transiting Exoplanet Survey Satellite
TSIP	Telescope System Instrumentation Program
UKIRT	UK Infrared Telescope
URO	University Radio Observatory
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VLT	Very Large Telescope
WFIRST	Wide-Field Infrared Survey Telescope
WIMPS	Weakly Interacting Massive ParticleS
XARM	X-ray Astronomy Recovery Mission
XRP	Exoplanet Research Program