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14 March 2024

The Honorable Sethuraman Panchanathan, Director
U.S. National Science Foundation
2415 Eisenhower Avenue, Suite 19000
Alexandria, VA 22314

The Honorable Bill Nelson, Administrator
Office of the Administrator
NASA Headquarters
Washington, DC 20546-0001

The Honorable Jennifer Granholm, Secretary
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

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

The Honorable Maria Cantwell, Chairwoman
Committee on Commerce, Science and Transportation
United States Senate
Washington, DC 20510

The Honorable Bernard Sanders, Chair
Committee on Health, Education, Labor & Pensions
United States Senate
Washington, DC 20510

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Center for Astrophysics | Harvard & Smithsonian
60 Garden St., MS 45
Cambridge, MA 02138

Dear Director Panchanathan, Administrator Nelson, Secretary Granholm, Chairman Lucas, Chair Cantwell, and Chair Sanders:

I am pleased to transmit to you the annual report of the Astronomy and Astrophysics Advisory Committee for 2023–2024.

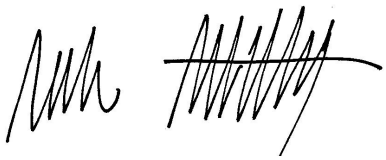
The Astronomy and Astrophysics Advisory Committee was established under the National Science Foundation Authorization Act of 2002 Public Law 107-368 to:

(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, the National Aeronautics and Space Administration, and the Department of Energy as they relate to the recommendations contained in the National Research Council's 2021 report entitled "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," 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 NSF Director, the Administrator of the National Aeronautics and Space Administration, the Secretary of Energy, the Committee on Science of the House of Representatives, the Committee on Commerce, Science and Transportation of the United States Senate, and the Committee on Health, Labor, and Pensions of the United States Senate on the Advisory Committee's findings and recommendations under paragraphs (1) and (2).

The attached document is the twentieth 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. The report is also being sent to other Congressional Committees of Jurisdiction.

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

Sincerely yours, on behalf of the Committee,



Dr. Michael McCarthy
Chair, Astronomy and Astrophysics Advisory Committee

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Cc: The Honorable Zoe Lofgren, Ranking Member, Committee on Science, Space, and Technology, United States House of Representatives
The Honorable Ted Cruz, Ranking Member, Committee on Commerce, Science and Transportation, United States Senate
The Honorable Bill Cassidy, Ranking Member, Committee on Health, Education, Labor & Pensions, United States Senate
The Honorable Jeanne Shaheen, Chairwoman, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate
The Honorable Jerry Moran, Ranking Member, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate
The Honorable Joe Manchin III, Chairman, Committee on Energy & Natural Resources, United States Senate
The Honorable John Barrasso, Ranking Member, Committee on Energy & Natural Resources, United States Senate
The Honorable Jeff Duncan, Chairman, Subcommittee on Energy, Climate, and Grid Security, Committee on Energy and Commerce
The Honorable Diana DeGette, Ranking Member, Subcommittee on Energy, Climate, and Grid Security, Committee on Energy and Commerce
The Honorable Hal Rogers, Chairman, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives
The Honorable Matt Cartwright, Ranking Member, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives
The Honorable Patty Murray, Interim Chair, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate
The Honorable John Kennedy, Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate
The Honorable Chuck Fleischmann, Chairman, Subcommittee on Energy and Water Development, Committee on Appropriations, United States House of Representatives
The Honorable Marcy Kaptur, Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies, Committee on Appropriations, United States House of Representatives
Dr. Karen Marrongelle, Chief Operating Officer, Office of the Director, U.S. National Science Foundation
Dr. Linnea Avallone, Chief Officer for Research Facilities, Office of the Director, U.S. National Science Foundation
Dr. Denise Caldwell, Acting Assistant Director, Directorate for Mathematical and Physical Sciences, U.S. National Science Foundation
Dr. Tie Luo, Deputy Assistant Director, Directorate for Mathematical and Physical Sciences, U.S. National Science Foundation

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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
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Dr. Avital Bar-Shalom, Program Examiner, DOE, Office of Management and Budget
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Dr. Saul Gonzalez, Division Director, Physics Division, U.S. National Science Foundation
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Ms. Amanda Greenwell, Head, Office of Legislative and Public Affairs, U.S. National Science Foundation
Mr. Robert Moller, Deputy Office Head, Office of Legislative and Public Affairs, U.S. National Science Foundation
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Astronomy and Astrophysics Advisory Committee Members:

Dr. Darcy Barron, University of New Mexico
Dr. Alyson Brooks, Rutgers University
Dr. Wenda Cao, New Jersey Institute of Technology
Dr. Sarah Hörst, Johns Hopkins University
Dr. Nikole Lewis, Cornell University
Dr. Britt Lundgren, University of North Carolina Asheville
Dr. Raffaella Margutti, University of California - Berkeley
Dr. Michael McCarthy, Center for Astrophysics
Dr. Willie Rockward, Morgan State University
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Astronomy and Astrophysics Advisory Committee Annual Report for 2023–2024

As outlined in its charter, the purview of the Astronomy and Astrophysics Advisory Committee (AAAC) is in two areas: (1) to review and make findings and recommendations regarding the coordination of astronomy and astrophysics projects between DOE, NSF, and NASA, and (2) to assess and make recommendations to the same three agencies related to the most recent National Academies of Sciences, Engineering, and Medicine Decadal Survey report titled "Pathways to Discovery in Astronomy and Astrophysics for the 2020s" (Astro2020),[1] which was released in November 2021. Astro2020 has now been in the public domain for more than two years, and sufficient time has elapsed for a meaningful assessment of the three agencies' responses and actions to this consequential document to be undertaken. This report represents the annual summary of the current committee's findings, comments, and recommendations.

Executive Summary

DOE, NASA, and NSF have made clear and tangible progress in supporting the foundational activities that are essential to the health of the field of astronomy during the past 12 months: they have actively pursued new workforce initiatives and opportunities for all Americans, supported research projects to expand our knowledge and understanding of the cosmos, and engaged in technology programs to address challenges and opportunities in the field of astronomy and astrophysics, which increasingly include software in addition to hardware. Such activities are central to Astro2020 as they provide a firm foundation on which to build and harness the next generation of ground- and space-based initiatives endorsed by the Survey. The science highlights from the three agencies during the past year have been very impressive.

The agencies are also applauded for their efforts in supporting ongoing facilities and their operations during a period of considerable budget uncertainty while also maturing the scientific and technical readiness of large new facilities and missions outlined in Astro2020. As federal support for science has come under considerable long-term pressure, in which resource levels may remain highly constrained for an extended period of time, significant effort will be needed to support the most critical research programs, while making targeted, strategic investments in new facilities and capabilities. However, with careful planning, execution, and interagency coordination and external partnerships, as appropriate, the AAAC is confident that many of the most ambitious scientific objectives set forth by Astro2020 remain within our reach and control.

The AAAC reviewed the progress made by the three agencies toward realizing the highest priority next-generation facilities and missions, as described in Astro2020. This report calls particular attention to the status of the US Extremely Large Telescope (ELT) Program, the highest priority new ground-based

[1] https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

facility, and NSF, as the funding agency tasked with supporting this program. While the Astronomical Sciences (AST) Division and the Mathematical and Physical Science (MPS) Directorate have made significant progress in advancing this project closer to a decision point of construction during the past 12 months, long-standing structural issues as to how the cost of large facility projects are apportioned and supported within MPS are highlighted. The Committee remains steadfast in the belief that the US ELT Program is essential for continued American competitiveness and scientific leadership in astronomy; Europe has already begun construction of a 30-m class telescope, and China has announced ambitious and expansive plans to become a global leader in space research and science.

On a national level astronomy has a special — perhaps unique — ability to create formal and informal science education opportunities and engage the public, as evidenced by the fact that discoveries supported by the AST Division commonly rank as the most-read news stories from NSF year-over-year. No other Division at NSF can boast this sustained level of engagement. As the nation's top science and engineering talent development agency, the NSF is uniquely positioned to develop and expand the domestic workforce by increasing STEM skills and opportunities for all Americans, especially those from groups that have been historically excluded, provided it continues to invest, build, and manage ambitious facilities that expand the frontiers of knowledge.

The AAAC report also highlights five high-priority topics that require interagency coordination, cooperation, or engagement based on material presented by the agencies at public forums during the past year. These are

- Building and Sustaining a Technologically Innovative Workforce
- Prioritizing Laboratory Astrophysics to Advance Discovery
- Time Domain and Multi-Messenger Astrophysics
- Protecting Dark and Quiet Skies
- Establishing Consistent Demographic Standards

Findings and recommendations for laboratory astrophysics receive special attention in this report in light of a report that was submitted by the Laboratory Astrophysics Task Force (LATF) to the AAAC in February 2024, and formally endorsed by the AAAC at its public meeting on February 23, 2024. The LATF was established in February 2023 by the AAAC at the request of the NSF and NASA to address Astro2020's recommendations on this subject. The LATF report emphasizes the critical role that laboratory astrophysics plays in realizing the scientific return of missions and observatories. The importance of developing the laboratory astrophysics workforce through early career support and long-term job opportunities is highlighted. High-level recommendations include increased access to funding opportunities, long-term support for the curation and development of databases, and improved communication and collaboration among laboratory astrophysics users and providers to maintain the United States' competitiveness in this field. The full LATF report will be posted to the AAAC website.

The report concludes by highlighting two other topics of considerable and continued interest to the astronomical community: data infrastructure, a topic of escalating importance given rapid increases in

the data acquisition rates from new facilities, in which petabyte-scale data sets are becoming commonplace, and sustainability because many astronomical facilities are located in extremely remote locations where conventional energy sources are cost prohibitive, impractical, and/or environmentally unfriendly. In both instances, the AAAC finds there are real opportunities for the astronomical community to continue to play a leadership role in developing cross-cutting and innovative programs and serve as an exemplar to the larger science community and the public.

Conflict of Interest Disclosure

The AAAC is committed to ensuring that our annual report is both fair and balanced. For this reason, it is obligatory to identify and disclose any potential conflicts of interest (COIs) that could influence the perspectives and judgments, whether they be personal or institutional. To maintain the integrity of our analysis and the trust of our audience, the content on each major topic in our report was reviewed and approved by one or more members of the AAAC Committee who have no personal or institutional conflict.

Below, we provide a detailed summary of the potential conflicts of interest identified among our members. In alphabetical order: Barron, Margutti, McCarthy, Vieregg, and Zabludoff:

Barron:
Personal COI: A member of CMB-S4 collaboration.
Institutional COI: Associated with an institution involved in the ngVLA.

Margutti:
Personal COI: Leads the multi-messenger follow-up group within the Vera C. Rubin/LSST TVS collaboration.
Institutional COI: Institutional conflict with the US-Extremely Large Telescopes program (ELT, TMT).

McCarthy:
Personal COI: None stated with respect to the Decadal recommendations.
Institutional COI: As part of the CfA, involved in one of the US ELTs (GMT), the CMB-S4 project, the next generation Very Large Array (ng VLA), and NASA's Chandra X-ray Observatory.

Vieregg:
Personal COI: A member of CMB-S4 collaboration.
Institutional COI: Associated with institutions involved in the US ELT program (GMT) and the CMB-S4 projects.

Zabludoff:
Personal COI: None explicitly stated with the US-ELT program; however, there is a conflict with the NSF AI Astro Institute call due to leading one of the proposal teams.
Institutional COI: Institutional conflict with the US-ELT program (GMT).

By making this disclosure, we hope to ensure that the insights and conclusions presented in the AAAC report are informed by an objective and comprehensive analysis, and not influenced by personal or institutional biases.

I. Agency and Science Highlights

DOE Office of Science, Office of High Energy Physics

The Vera C. Rubin Observatory, a joint partnership with NSF and the flagship project in DOE's Office of High Energy Physics and the Cosmic Frontiers portfolio, remains on schedule for first light in 2025. In 2024, the Camera will be transported to Chile, and images will be obtained with the Commissioning Camera. In early 2025, images will be collected with the Legacy Survey of Space and Time (LSST) Science Camera, with the 10-year survey commencing later in the year. LSST and the Dark Energy Spectroscopic Instrument (DESI) will provide unprecedented constraints on the nature of cosmic acceleration using probes of structure growth and the cosmic expansion rate. This program will be particularly powerful when combined with complementary data sets, e.g., from Euclid, NASA's Nancy Grace Roman Space Telescope, and CMB-S4.

In December 2023, the much-anticipated Particle Physics Project Prioritization Panel (P5) report was released and formally accepted by both DOE and NSF. It lays out a vision for US Particle Physics for the next 10 years in a 20-year context and two constrained budget scenarios. The scientific goals laid out in the P5 report for the US Particle Physics program are to Decipher the Quantum Realm, Illuminate the Hidden Universe, and Explore New Paradigms in Physics. It is worth emphasizing that the P5 report emphasizes the interdisciplinary nature of astronomy, cosmology, and particle physics, with many of its science goals dovetailing with topics covered by and endorsed in Astro2020.

The top new major project recommendation in the P5 report is the Cosmic Microwave Background Stage-IV experiment, CMB-S4, which was also listed as a high priority in Astro2020. CMB-S4 will look back at the earliest moments of the universe to probe the physics of inflation, has unprecedented sensitivity to light relics in the early universe, and will open an exciting new window into millimeter-wave astrophysical transient science. The P5 report also endorses continuing support for DESI and LSST and endorses construction of DESI-II. In addition, R&D for a future spectroscopic survey, Spec-S5, and for Line Intensity Mapping (LIM) observatories is endorsed by P5. DOE is expected to begin implementing the latest P5 report in earnest in 2026.

NASA Astrophysics Division

NASA's Astrophysics Division reached a number of major milestones during the past year that advance our understanding of the universe from space. Three missions were successfully launched: Euclid, XRISM, and GUSTO, and three missions are producing significant scientific impact and outcomes in their prime mission: JWST, Euclid, and SXG. Euclid, a European Space Agency mission with important contributions from NASA, launched in July of 2023. It will employ a wide-angle camera operating in the

visible portion of the spectrum, a near-infrared spectrometer, and a photometer to precisely measure the redshift of galaxies and better understand dark energy and dark matter on universal scales. The X-ray Imaging and Spectroscopy Mission (XRISM) is an X-ray space mission led by the Japan Aerospace Exploration Agency in partnership with NASA and the European Space Agency. It launched in early September 2023, and will investigate the properties of gas within galaxy clusters, the process of chemical enrichment throughout the Universe, and the extreme physics surrounding the accretion of supermassive black holes over its three years of operations. First light results from its two instruments (an imager and spectrometer) released in January 2024, indicate excellent performance. GUSTO is a balloon mission that launched Dec. 31, 2023, from McMurdo, Antarctica. It is expected to stay aloft for two months, potentially longer, depending on weather conditions. Using detectors at terahertz wavelengths, it will detect emission lines of atomic carbon, oxygen, and nitrogen in the interstellar gas in our Milky Way galaxy to map out the lifecycle of these key elements in the space between stars.

Significant progress towards completion of SPHEREx, a future near-infrared space observatory, has been made, with the telescope and optics now undergoing rigorous thermal and vacuum testing, and the Photon Shields successfully completed vibration testing. This observatory, scheduled to launch no later than April 2025, will perform an all-sky spectral survey in the near-infrared of more than 490 million galaxies to determine how our universe evolved; it will also detect more than 90 million stars in the Milky Way to understand the origin of water — a key molecule in life as we know it — in planetary systems.

The next Flagship astrophysics mission, the Nancy Grace Roman Space Telescope, remains on schedule to launch in 2027. During the past 12 months, a notable highlight has been instrument integration of the Wide Field Instrument (WFI) and the Coronagraph Instrument (CGI), with environmental testing now underway. WFI is a multi-band visible and near-infrared camera that will produce images of comparable sharpness to those produced by the Hubble Space Telescope, but with a field of view 100 times larger, allowing astronomers to address key questions in the areas of dark energy, exoplanets, and infrared astrophysics. Preliminary test results indicate excellent performance of the WFI, well-exceeding system requirements both in terms of background noise and wavefront error. Important milestones for Roman in 2024 include a Systems Integration Design Review (SIR) and Key Decision Point-D (KDP-D). In 2023, the incredible success of JWST, which is roughly 18 months into its 5-year prime mission, continues unabated, with high-profile discoveries announced regularly. A clear indication of its value to the astronomical community is evidenced by the sheer number of proposals received for Cycle 3 observations: 1931, well exceeding the number for any prior mission.

NSF Astronomical Sciences Division

In the past year, NSF's Astronomical Sciences Division (AST) has made significant progress on facility and workforce development.

The recently inaugurated Daniel K. Inouye Solar Telescope (DKIST), the most powerful solar optical telescope on Earth, began its Operations Commissioning Phase (OCP). This period marks a learning and transitioning period from construction to operations from both a technical- and science-operations perspective. The international science community was invited to participate in the OCP effort by submitting and executing science proposals. The released data from the DKIST Cycle 1 operation window has revealed record-breaking observational capabilities, with a resolving power equivalent of seeing a $1 coin in New York from Boston, heralding a new era that promises to revolutionize our understanding of the Sun, its magnetic behavior, and its influence on Earth. With the DKIST Cycle 1 data, an international team has stepped closer to understanding one of the most enduring solar mysteries: why the corona (the outermost layer of the Sun) is hundreds of times hotter than the photosphere (the innermost layer of the solar atmosphere). DKIST is currently collecting data for the Cycle 2 scientific proposals, while its Data Center continues calibrating and delivering data to the solar physics and space science communities. More new and exciting results are expected soon for spectacular views of our solar system's most influential celestial body.

In March 2023, the Atacama Large Millimeter/submillimeter Array (ALMA), the world's largest radio telescope, celebrated 10 years of operation. This facility continues to conduct a wide array of exquisite observations that no other telescopes on Earth can match, enabling research on topics ranging from planet formation to the physical properties of galaxies in the early universe. Proposals and the time requested to perform new observations remain heavily oversubscribed.

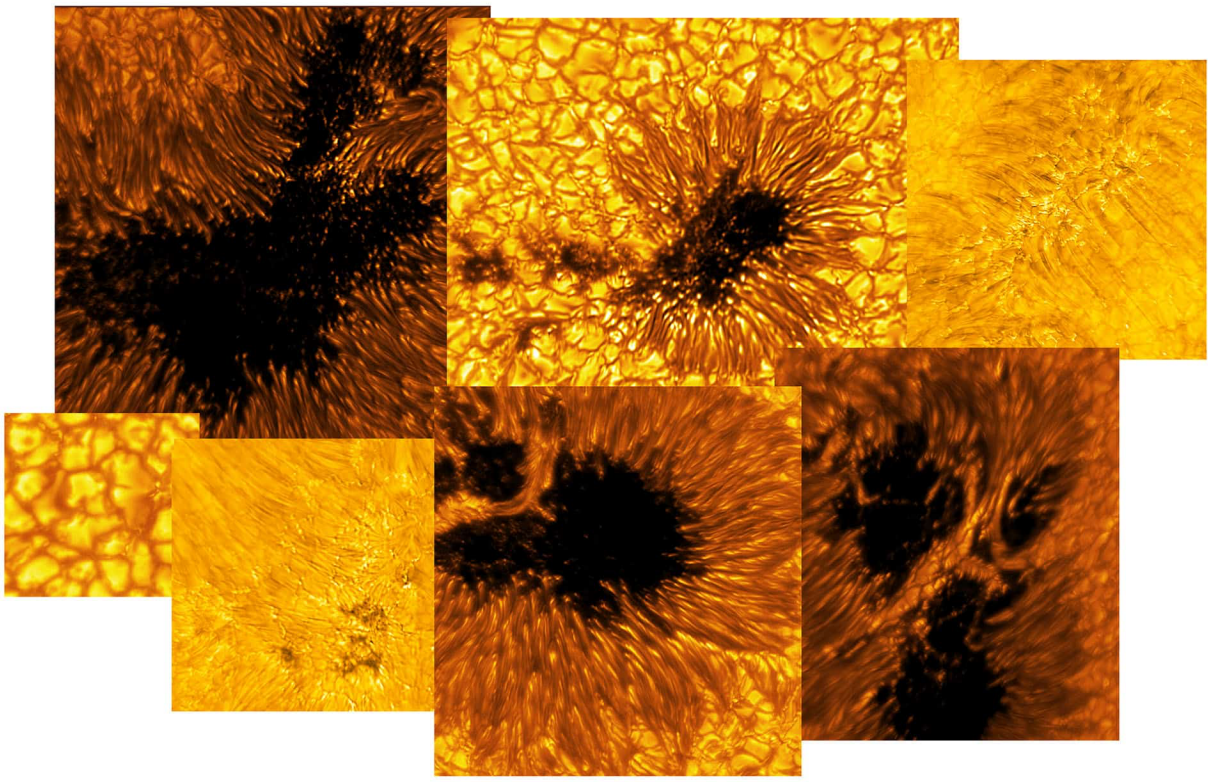
Other highlights include milestones in the development of new major facilities: the US ELT Program completed NSF's Preliminary Design Review early in 2023 and is seeking approval from the Facilities Readiness Panel to proceed to the Final Design phase; the ngVLA entered the NSF's Major Facility Design Stage (in Conceptual Design Phase) in July 2023.

NSF announced new efforts in workforce development to foster a diverse, inclusive, and equitable environment for astronomy and astrophysics research and education. For example, the new PAARE/AST program encourages partnerships between institutions with underrepresented groups that provide pathways into research; and LEAPS/MPS helps launch the careers of pre-tenure faculty at institutions that do not traditionally receive significant NSF funding. These initiatives complement a number of ongoing AST/MPS/NSF programs devoted to training a diverse workforce and enhancing opportunities for early career researchers.

Science Highlights

The past year has been a period of remarkable discovery, scientific output, and impact across all three agencies. Beyond the purely scientific value to researchers, these discoveries continue to illustrate astronomy's special — perhaps unique — role in connecting science with the general public and the opportunities it can create for formal and informal science education and engagement. The top research

news story across all of NSF in 2023 was from the AST Division[2]: the unambiguous detection of a dormant stellar-mass black hole in the Milky Way using the Gemini North Telescope in Hawaii. This black hole is estimated to be 10 times more massive than the Sun, and in terms of astronomical scales, is relatively close to Earth, located only about 1,600 light-years away — three times closer than the next closest known black hole. We note this level of notoriety is common for the AST Division. In 2022, three of the top ten most-read research news stories were from AST,[3] and in 2021, the detection of polarized light from the edge of a black hole at the center of the galaxy M87 ranked as the second most impactful development across all of NSF.[4]



Eight new images showcasing a mix of sunspots and tranquil solar regions which the Inouye Solar Telescope captured during its first year of commissioning. Image credit: NSF/AURA/NSO

NASA's JWST continues to make discoveries and produce stunning images almost weekly. As of December 2023, only 18 months after first light, over 450 articles have been published in peer-reviewed journals with "JWST" in the title. Among many possible highlights, the discovery of two carbon-bearing molecules, methane (CH4) and carbon dioxide (CO2), in an exoplanet (K2-18 b)[5] is particularly noteworthy as it may indicate a so-called Hycean planet, one with a hydrogen-rich atmosphere and a surface covered in whole or in part by liquid water. Recent observations from NASA's Imaging X-ray Polarimetry Explorer (IXPE) and the Chandra X-ray Observatory suggest that X-ray emissions of giant gas

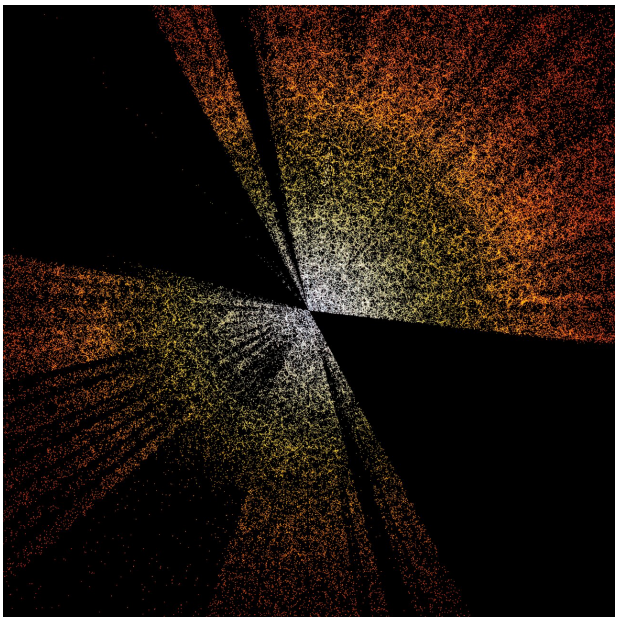
[2] https://content.govdelivery.com/accounts/USNSF/bulletins/380d69a
[3] https://content.govdelivery.com/accounts/USNSF/bulletins/33ebb67
[4] https://new.nsf.gov/science-matters/nsf-year-discovery-innovation
[5] https://www.nasa.gov/universe/exoplanets/webb-discovers-methane-carbon-dioxide-in-atmosphere-of-k2-18-b/

clouds in the vicinity of Sagittarius A* – the supermassive black hole at the center of our Milky Way galaxy – are likely the result of scattered light from a short intense flare produced by this black hole roughly 200 years ago. Due to the circuitous path the light took, it is only being detected now.

A high-resolution near-infrared image from JWST showing the young, actively forming star pair Herbig-Haro 46/47, marked by red diffraction spikes and an orange-white core, the pair is encased in a gas and dust disc. The surrounding nebula and two-sided jets highlight the dynamic mass accumulation and ejection processes shaping these stars. Image credit: NASA, ESA, CSA.

Through 2023, roughly two and one-half years into its official five-year run, DESI has collected the redshifts of more than 26 million galaxies, quasars, and stars, with another 100,000 objects added nightly; the ultimate goal is to collect redshifts of 40 million objects. In June 2023, the collaboration released to the scientific community nearly two million objects detected during the experiment's survey validation phase, along with a tranche of papers using the early data release, including the results of the 'one percent' survey, which resulted in a 3D map representing roughly 1% of the total volume of the survey with 700,000 objects imaged from 20 directions in the sky. The Dark Energy Survey (DES), a DOE/NSF partnership, mapped an area of almost one-eighth of the sky over its six-year survey, which ended in January 2019. Early in 2024, the international collaboration released cosmology results[6] that included about 1500 new high-redshift type Ia supernovae from a 5-year dataset. The results from this analysis are consistent with a Lambda Cold Dark Matter (ΛCDM) universe in which the density of dark energy is constant over cosmic time, but a more complex model has not been ruled out.

[6] https://www.interactions.org/press-release/final-supernova-results-dark-energy-survey-offer-unique



A cross-section of the 3D galaxy map from the initial few months of the DESI survey with Earth at the center. The map extends up to about 10 billion light-years away, with each dot indicating a galaxy. Image credit: D. Schlegel / DESI / Lawrence Berkeley National Laboratory / M. Zamani, NSF's NOIRLab.

II. Findings and Recommendations

A. High-priority Topics Requiring Interagency Coordination, Cooperation, or Engagement

1. Building and Sustaining a Technologically Innovative Workforce

Astro2020 places great emphasis on the critical role of foundational activities in astronomy and astrophysics, focusing on the integration of community engagement, diversity enhancement, and technological innovation. In particular, it stresses the need for increased investment in STEM education and initiatives that broaden participation in astronomy to maintain US leadership in science and technology.

Finding: The HEPAP International Benchmarking Study report,[7] delivered to the DOE and NSF in November 2023, provided specific recommendations for workforce development to meet the decadal priorities of the particle physics community. These recommendations align closely with many of those on this topic in Astro2020.

Finding: The number of US students obtaining a bachelor's degree in astronomy has more than doubled over the past ten years[8], indicating that press releases and other public outreach from the agencies'

[7] https://science.osti.gov/-/media/hep/hepap/pdf/202311/HEPAPBenchmarking_Nov_2023.pdf
[8] https://aip.brightspotcdn.com/37/79/db9f3666ea0129f8b9970cba15f0/astrost22.pdf

supported missions, observatories, and experiments are driving public interest in science generally and astronomy specifically.

Finding: Internships and Research Experiences for Undergraduates (REU) programs supported by NASA, NSF, and DOE provide critical opportunities for undergraduate students from a variety of institutions and demographics across the US to engage in research and build highly transferable skills in software development, instrumentation, and analytics.

Finding: As the nation's science and engineering talent development agency, NSF should be applauded for its investment in a plethora of workforce development grant programs (e.g., ASCEND, GRANTED, etc.) at the Division, MPS, and NSF-wide levels, many targeting institutions with few resources and limited research activities. Of particular note is the recently expanded PAARE program, which offers partnership opportunities to a larger number of institutions and greater flexibility to support both incipient and fully formed partnerships; and LEAPS, an MPS program, which supports pre-tenure faculty predominantly at undergraduate or R2 institutions. DOE offers similar opportunities through its RENEW and FAIR grants.

Recommendation: All three agencies should continue to prioritize the development and promotion of new education and workforce initiatives, as these opportunities play a critical role in developing a diverse and skilled talent pool, essential for advancing the frontiers of science and technology.

Recommendation: The agencies should continue to emphasize a Community Astronomy approach in their planning and programs, as highlighted in Astro2020, to foster lasting partnerships with Indigenous and local communities that are of mutual benefit, are culturally inclusive, and highly value sustainable site stewardship. Doing so provides increased opportunities for all Americans while strengthening the value and trust placed in the agencies as responsible partners.

Finding: The rise in the number of astronomy bachelor and undergraduate research opportunities has led to a two-fold increase in applications to astronomy Ph.D. programs over the past ten years. However, available openings in these programs, which are largely dictated by the roughly flat funding of individual investigator grants, have only increased by ~30% in the same timeframe.

Recommendation: Individual investigator grant programs and key programs devoted to training a diverse workforce and enhancing early career researchers must be prioritized in any budget scenario to ensure a healthy pool of skilled practitioners in astronomy. In this context, the agencies should review what resources could or should be harnessed to support "bridge" programs (before and after college) to strengthen skill retention across junctures in the higher education pathway, as well as to promote growth in Ph.D. programs so as to keep pace with the rising number of qualified undergraduates.

Finding: Many new astronomy PhDs are accepting positions with long-term employment prospects in the private sector, which offer nearly double the median starting salary of an academic postdoc[9]. More than half of the private sector positions accepted by new astronomy PhDs are in the areas of software development, data science, and engineering, indicating the high transferability of a graduate-level astronomy education to the broader economy and workforce.

Finding: Computing-intensive research investments in astronomy increasingly struggle to retain experienced PhDs, due to competition with the private sector. This challenge in retaining graduates, especially those trained in artificial intelligence and machine learning, is shared by the particle physics community, as detailed in the 2023 HEPAP Benchmark Study report.

Recommendation: The agencies should continue to provide scientific and technical opportunities that expand the frontiers of knowledge, are ambitious and innovative, have the potential to be transformative, and inspire the future US workforce to meet the needs of the field while advancing the private sector.

Finding: Some of the most important national initiatives and strategy reports on topics such as Artificial Intelligence (AI), Quantum Information Science, and Microelectronics Research are very well aligned with activities or programs already underway at NASA, NSF, and DOE to help address the most exciting and vexing questions in astronomy. Both DOE and NSF are prominently mentioned in these reports, and both have current or new funding opportunities in these strategic areas, specifically in astronomical sciences (e.g., NSF's AI Research Institute for Astronomical Science). NASA is also heavily involved in such initiatives: its Space Technology Mission Directorate (STMD) supports and develops transformative space technologies to enable future missions and AI has been used to design mission hardware and spacecraft [e.g., the EXoplanet Climate Infrared TElescope (EXCITE) mission]. Missions such as the Habitable World Observatory will almost certainly require the development of new technologies and capabilities to address stringent technical requirements. Such pursuits drive innovation broadly, contribute to the nation's economy, and produce tangible benefits in real-world applications.

Recommendation: Given their expertise in many emerging technologies, as key players in the scientific landscape of the United States, and to ensure that the ongoing work of all three agencies is properly recognized, the AAAC encourages agency involvement as stakeholders and potential contributors in proposed round tables, groups and collaboration activities of national strategic interest, such as that outlined in the CHIPS for America Act and its Subcommittee on Microelectronics Leadership.

2. Prioritizing Laboratory Astrophysics to Advance Discovery

Laboratory astrophysics plays a key role in astronomical and planetary sciences. This broadly defined field consists of a wide range of laboratory experiments (e.g. spectroscopy, kinetics, surface science), as well as theoretical calculations and modeling. It covers almost the entire electromagnetic spectrum,

[9] https://ww2.aip.org/statistics/new-astronomy-phds-what-comes-next

from radio to gamma-rays, and involves atomic, molecular, nuclear, plasma, and solid-state systems. Such studies provide the fundamental basis for interpreting astronomical observations in almost all fields and allow for new scientific advances. Such data are particularly needed now, as observatories such as the Atacama Large Millimeter Array (ALMA), JWST, DKIST, and LSST reach full operational capacity, generating an enormous volume of data that needs interpretation. As highlighted in the Astronomy & Astrophysics 2020 Decadal Survey:

> *"Laboratory astrophysics is a critical but often hidden and underappreciated cornerstone of the enabling research foundation. It has been chronically underfunded; concerns were raised in both the 2000 and 2010 decadal surveys, but the problem persists. Research in this area needs to be regarded as a high priority, and the existing approaches are not sufficiently advancing the field."*

Decadal recommendation: *NASA and the National Science Foundation should (1) convene a broad panel of experts to identify the needs for supporting laboratory data to interpret the results from the new generation of astronomical observatories, (2) identify the national resources that can be brought to bear to satisfy those needs, and (3) consider new approaches or programs for building the requisite databases. This panel should include experts in laboratory astrophysics as well as representative users of the data, who can best identify the highest-priority applications.*

At the request of NSF and NASA, the AAAC convened the Laboratory Astrophysics Task Force (LATF) in February 2023 to further examine the challenges and needs currently facing this community and report findings and recommendations to the AAAC in early 2024. The following is a summary of findings and recommendations from the LATF report in the areas of Funding, Workforce Development, Databases, Facilities and Resources, and Interdisciplinary Communication and Collaboration. The full report is appended to the end of this document.

Funding

Finding #1: There is no program at NSF, NASA, or DOE that funds laboratory astrophysics as its primary objective. Additionally, there is limited support for laboratory astrophysics in programs currently funded by the agencies. For example, programs that currently fund laboratory astrophysics at NASA (APRA, ADAP) explicitly exclude exoplanet research. Exoplanet laboratory research is funded only by the Exoplanets Research Program (XRP) at NASA which has a lower selection rate than APRA and ADAP[10].

Finding #2: Although laboratory astrophysics is essential in maximizing the scientific potential and impact of astronomical missions and observatories, funding to support these efforts is not a formal part of mission planning and long-term mission support.

[10] https://science.nasa.gov/wp-content/uploads/2024/01/septembergrantstatsv2-tagged.pdf

Recommendation #1: The agencies should increase access to funding opportunities in laboratory astrophysics for both single PI-led programs and larger collaborative teams by developing joint programs and, where necessary, expanding the scope of current proposal calls to explicitly include laboratory astrophysics efforts. NASA and NSF should explore joint and collaborative programs to meet common needs in the community, and as needed, pursue separate laboratory astrophysics funding lines to ensure sustained support for the critical enabling efforts of laboratory astrophysics.

Recommendation #2: Laboratory astrophysics should be explicitly incorporated in all phases of a facility or mission from planning to extended operations. It is recommended that an appropriate amount of the total cost of large NSF and NASA-funded observatories and missions should be invested in laboratory astrophysics work to ensure its scientific output and impact. An example would be the use of the ALMA Development Fund for Lab Astro projects.

Recommendation #3: The agencies should consider expanding certain programs that are beyond the scope of individual PIs to create and support modest-sized instrumentation or facility centers that provide professional and centralized services to the laboratory astrophysics community. Examples include NSF's National Facilities and NASA's Planetary Science Enabling Facilities (PSEF). The NSF-UCLA Secondary Ion Mass Spectrometry (SIMS) (https://uclasims.epss.ucla.edu/) facility is an efficient and inclusive model that can be adapted.

Workforce Development

Finding #3: To maintain competitiveness at the international level in the STEM fields, the United States must develop a workforce with critical-thinking skills, deep scientific understanding, and experience in hands-on laboratory skills and data science. Training in laboratory astrophysics is an ideal vehicle for developing these critical skills. The current laboratory astrophysics workforce is aging and current PIs at NASA centers and Universities do not have the resources and/or access to students required to prevent the workforce from dwindling further by training and retaining the next generation.

Finding #4: NSF provides a variety of workforce development grant programs (e.g., ASCEND, GRANTED, PAARE, LEAPS) at the AST Division, MPS, and NSF-wide levels, many targeting institutions with few resources and limited research activities, e.g., NSF Partnerships in Astronomy and Astrophysics Research and Education program. However, it appears that few practitioners in laboratory astrophysics have been able to pursue these funding opportunities to leverage their research capacity.

Recommendation #4: NASA and NSF should continue to prioritize and promote workforce development initiatives spanning the career progression from undergraduate to the early-career level and consider how these opportunities could be adapted to support the specific needs of the laboratory astrophysics community.

Databases

Finding #5: The numerous laboratory astrophysics databases that the broader astronomical community increasingly relies upon do not have the modest consistent funding support for maintenance, updates/upgrades, and user interactions and support.

Finding #6: Although there are numerous databases spanning a wide range of types of laboratory data, most of them are not complete (e.g., temperature, wavelength, chemical species, uncertainties) to the level needed by the astronomical community.

Recommendation #5: Approaches for long-term support for the curation and development of the existing databases with emphasis on critical data evaluation and uncertainty quantification should be pursued. This support should include the specialized database workforce as well as resources to connect and search the databases.

Recommendation #6: It is recommended that a "Database of Databases" and "Database of Facilities" are created to bring awareness to what is available in the scientific communities and enable collaborations.

Facilities and Resources

Finding #7: The infrastructure that supports laboratory astrophysics is a complex network of interconnecting parts, each of which cannot advance significantly without the others.

Finding #8: Laboratory astrophysics is a diverse field, ranging from fundamental investigations of phenomena to more applied studies.

Finding #9: The astronomical community has historically benefited from studies and data produced in related fields, primarily Chemistry, Earth Sciences, and Physics, which have been supported by these disciplines. With the shifting priorities in these core disciplines, this level of support has diminished over time. Increasingly, the astronomical community will need to fund these activities to better understand observations from facilities and missions.

Recommendation #7: Because laboratory astrophysics is a highly interdisciplinary enterprise, the agencies should thoroughly explore opportunities for interagency coordination to streamline allocation of resources that support critical experimental facilities. Doing so would allow for more strategic investments to meet the common needs of current and future missions. For example, NASA and NSF-funded projects could effectively leverage resources that exist at DOE facilities (e.g., EBIT plasma experiments, synchrotron light sources).

Interdisciplinary Communication and Collaboration

Finding #10: A lack of effective and meaningful communication between practitioners of laboratory astrophysics and the wider astronomical community has been identified.

Recommendation #8: The agencies should consider facilitating community meetings that highlight the interplay of laboratory astrophysics with forefront astronomical problems and promote meaningful interactions between astronomers who rely on laboratory astrophysics data and the researchers who generate and curate those data. Because laboratory astrophysics is uniquely positioned to bridge the gap between astronomy and numerous key subfields of chemistry and physics, the meetings should also highlight interdisciplinary efforts, synergies, as well as cross-disciplinary and interagency funding opportunities that could be leveraged to address critical data needs of current and proposed astronomical missions.

Global Recommendation: Given the importance that Astro2020 placed on laboratory astrophysics as a cornerstone of the enabling research foundation, and the explicit finding by Astro2020 that existing approaches are not advancing the field sufficiently, the AAAC and LATF recommend that the agencies provide an assessment of their progress toward addressing support for laboratory astrophysics prior to the mid-decadal NASEM Survey. This review is especially timely as the science drivers for planned flagship missions and observatories are defined in the next several years, and the needs of existing ones continue to evolve.

3. Time Domain and Multi-Messenger Astrophysics

Time Domain and Multi-Messenger Astrophysics (TDAMM) is a rich field that has grown quickly over the last decade and was highly recommended by Astro2020. Combining observations of gravitational waves, neutrinos, and photons across the electromagnetic spectrum from astrophysical sources opens new windows to the universe and yields new discoveries that an individual observatory alone is incapable of making. GW170817, a binary neutron star merger observed in gravitational waves by LIGO and VIRGO, as a gamma-ray burst by the Fermi Gamma-Ray Telescope, and subsequently by a suite of electromagnetic follow-ups, is a spectacular example of the rich scientific opportunity that is enabled by coordination among observatories.

Finding: TDAMM is intrinsically a multi-messenger (neutrinos, gravitational waves, photons), multi-wavelength, multi-observatory endeavor that happens on short timescales (sometimes as short as hours). This presents unique challenges to observatory coordination, scientific collaboration, and data management.

Finding: NASA organized a workshop in August 2022 to identify the top TDAMM science questions associated with the recommendations of Astro2020. A summary white paper[11] presents findings from the workshop, including a need for wide-field, fast-response X-ray and gamma-ray monitors with arcminute resolution.

Finding: Subsequently, NSF NOIRLab hosted a workshop in October 2023 titled "Windows on the Universe: Establishing the Infrastructure for a Collaborative Multi-messenger Ecosystem" focused on establishing the infrastructure required for the inherently collaborative multi-messenger science. A white paper[12] summarized the workshop discussions and findings.

Finding: The field of TDAMM science will take a quantum leap forward when the LSST survey using the Vera Rubin Observatory begins in late 2025. It is estimated that 10 million alerts may be generated per night.[13]

Finding: Coordination of real-time observations over multiple facilities will improve the efficiency of time-domain observations. Without coordination at the time of proposals, competing (redundant) observations could be approved across different facilities. There are agreements between some facilities, but those agreements do not always extend to Target of Opportunity observations.

Recommendation: A coordinated plan should be developed between NSF and NASA for determining how TDAMM-related observations should be planned and triggered, and for making the data public. These efforts might be expanded to include joint software development and a common archive infrastructure. Coordination between ground- and space-based facilities is essential to realize the full potential of TDAMM science.

Finding: Owing to ongoing budgetary pressure, NASA recently announced significant budgetary cuts to the Guest Observer (GO) programs of both Hubble and Chandra in the current observing cycle. The size of these cuts to Chandra might imply this X-ray flagship mission will not be able to respond to Targets of Opportunity (ToO) or Director's Discretionary Time (DDTs) or do so with reduced capability. If so, the ability to perform TDAMM science will be negatively impacted.

Recommendation: Consistent with Astro2020 which identified TDAMM as the top space priority of the sustaining activities for the future decades, the AAAC encourages NASA to keep — and ideally increase — the ToOs and DDTs capabilities of existing observatories.

Recommendation: As TDAMM studies require a multi-wavelength approach, often utilizing facilities across the three agencies, the agencies should support and expand multi-agency opportunities for observing opportunities and grants that cover facilities operating throughout the electromagnetic

[11] https://pcos.gsfc.nasa.gov/TDAMM/docs/TDAMM_Report.pdf
[12] https://arxiv.org/abs/2401.02063
[13] https://iopscience.iop.org/article/10.1088/1538-3873/acdb9a

spectrum. ACROSS (NASA's Astrophysics Cross-Observatory Science support) and AEON (NOIRLab's Astronomical Event Observatory Network) are two pilot efforts that have begun to facilitate the planning and execution of TDAMM science cases but sustained funding and large-scale efforts will likely be needed.

Recommendation: NASA should develop a strategy by which TDAMM science is enabled across a suite of missions, as opposed to individual missions being considered on a stand-alone basis.

4. Protecting Dark and Quiet Skies

Astro2020 highlights the increasing challenge posed by very large satellite constellations to astronomical observations, particularly in optical wide-field imaging and the search for near-Earth objects. The Vera Rubin Observatory is among the facilities that will be significantly affected by optically bright satellites. Major investments in ground-based radio observatories such as the Very Long Baseline Array, which play a key role in not only astronomical science but also national security and global positioning system (GPS) calibration, are already impacted by radio emissions from satellites. This situation may dramatically worsen if satellite use of the terrestrial mobile spectrum is advanced without careful coordination. Astro2020 recommended that the NSF, in collaboration with federal agencies, develop a regulatory framework to mitigate the impact of satellite constellations on astronomy and the night sky. This effort should involve various stakeholders, including astronomers, regulatory bodies, satellite operators, and the public, with an emphasis on international coordination to address this global issue effectively.

Finding: The rapidly increasing number of satellites in low-Earth orbit (LEO) continues to impact astronomical observations across the electromagnetic spectrum, both on the ground and in space.

Finding: The increasing frequency of satellite conjunctions, and the increasing number of fragments from debris events, pose a growing threat to space-based observatories in LEO. NASA's Conjunction Assessment and Collision Avoidance group notes that the Hubble Space Telescope is already threatened by a possible conjunction with another satellite on a weekly basis.

Finding: Studies conducted by NASA and NSF's NOIRLab concur that despite reflection mitigation efforts by some of the major satellite operators, the current optical brightness of satellites remains above the 7th magnitude limit required to optimize the science from premier ground-based optical observatories, including Rubin. Furthermore, how reflection mitigation strategies might degrade over the lifetime of the satellites is also not yet known.

Finding: While currently considered only a nuisance by NASA's planetary defense program, an increasing frequency of satellite trails in observations of near-Earth asteroids may eventually impair our ability to detect impact hazards.

Finding: NSF has invested significant resources into international advocacy for spectrum regulation, which is achieving positive results for protecting sites and frequencies essential for radio astronomy. Important progress was made on these issues by the NSF delegation at the 2023 World Radio Conference and Radiocommunication Assembly, which will advance protections for radio quiet zones around NSF and DOE investments, including ALMA, SKA, and LuSEE-night. In coordination with the National Telecommunications and Information Administration, the NSF also submitted a comprehensive white paper in February 2024 to the Federal Communications Commission[14], detailing the risks to existing and future radio astronomy investments by satellite use of the terrestrial mobile spectrum and providing recommendations on how best to balance the extension of mobile radio coverage with the needs of radio astronomy facilities.

Finding: The bulk of satellite brightness data is currently collected through volunteer efforts (e.g., COMPASSE and Sathub), which lack the resources required to monitor the rapidly evolving situation and support effective advocacy and mitigation efforts.

Recommendation: The AAAC encourages NASA and NSF's NOIRLab to collaborate in monitoring the position and brightness of satellite constellations. Together the agencies can more effectively quantify the impact of these constellations and inform the advocacy work required to protect their scientific investments.

Recommendation: It would be beneficial to provide the community with more funding opportunities to support the essential task of monitoring satellites and mitigating their impact on astronomical observations across the electromagnetic spectrum.

Recommendation: The AAAC encourages NASA to leverage its expertise in satellite missions and collision avoidance to help quantify the carrying capacity of low-Earth orbit. By collaborating with NSF and DOE, NASA can play a pivotal role in assessing at what density satellite constellations might begin to adversely affect the crucial science objectives of existing and future astronomical surveys.

5. Establishing Consistent Demographic Standards

To enhance diversity in astronomy and astrophysics, Astro2020 advocated for NASA, NSF, and DOE to establish a joint committee to standardize and regularly share data on demographics and outcomes of proposal competitions, ensuring progress in inclusion and access can be measured and evaluated. The importance of achieving this goal is reinforced by the CHIPS and Science Act of 2022, which compels all federal science agencies to "collect comprehensive demographic data on recipients of federal grants and to report this data to NSF for summarization and publication."[15]

[14] https://www.fcc.gov/ecfs/filing/status/detail/confirmation/20240216961519697
[15] https://www.congress.gov/116/crpt/hrpt184/CRPT-116hrpt184.pdf#page=15

The HEPAP International Benchmarking Study report[16], presented to the NSF and the DOE in November 2023, also stressed the importance of providing more compelling, inclusive, and equitable opportunities for US citizens in particle physics. The report aligns with the previous recommendations of Astro2020 and AAAC reports by specifically recommending that NASA, NSF, and DOE collect and report statistics on the workforce, "track their evolution over time across levels: laboratories, collaborations, and nation-wide," and align the categorizations to enable "consistent comparison across different datasets."

Finding: NASA, NSF, and DOE have not made satisfactory progress toward the Astro2020 recommendation for a standardized collection and publication of PI demographics.

Recommendation: The AAAC concurs with the recommendations of the HEPAP Benchmarking report and continues — for the fourth consecutive year — to recommend that the agencies embrace consistent demographic collection and transparent reporting, which are critical for enabling data-informed approaches to improve diversity, equity, and inclusion in the profession.

Recommendation: The AAAC recommends the agencies draw guidance from successful examples of demographic data collection and reporting by the National Institutes of Health and the Space Telescope Science Institute.

Recommendation: If assistance from OMB is required to coordinate this effort across NASA, NSF, and DOE, it should be actively pursued by the agencies.

III. Astro2020 Decadal Recommendations

A. Ground-based Facilities

1. US Extremely Large Telescope (ELT) Program

The US ELT Program is the highest-ranked ground-based recommendation of Astro2020 and is essential for continued American scientific leadership in astronomy in the coming decade and beyond. Astronomy is a highly competitive and high-profile global enterprise, particularly as it relates to addressing the most fundamental and profound questions of humankind, such as "Are we alone?". To answer these questions and remain an international leader in astronomical discovery, a significant investment by the US in next-generation ground-based optical-infrared wavelength (OIR) facilities is required on a scale that exceeds historical funding levels.

The US ELT Program has two consortia, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), both of which seek to construct a 30-m class optical telescope in the coming decade.

[16] https://science.osti.gov/-/media/hep/hepap/pdf/202311/HEPAPBenchmarking_Nov_2023.pdf

The GMT is being built at Las Campanas in Chile, and the TMT aims to build on one of two potential sites in the northern hemisphere. Each consortium includes international partners, consistent with the National Science Board's guidance for the most complex and costly facilities, as presented in the NSB Vision 2030 Report[17].

A 39-meter aperture European ELT is already under construction in Chile's Atacama Desert, with first light expected in 2028. Without access to facilities of a similar scale in the near and long term, the U.S. astronomy community will be unable to lead discovery in nearly all of the key science priorities of Astro2020.

Finding: Following the release of Astro2020 in November 2021, Congress provided $30 M in augmentation funding to NSF in FY23 to address the goals of the Survey, with specific emphasis on the US ELT Program. In FY24, Congress again included language in the appropriations budget to provide NSF with $30 M in augmentation funding for the same purpose — clear signs of the continued value they place on this next-generation science capability.

Finding: The US ELT Program entered NSF's Major Facility Design Stage (in Preliminary Design Phase) in Dec 2022, and both the TMT and GMT successfully completed NSF's Preliminary Design Review process early in 2023. Moreover, the NSF MPS Blue Ribbon Panel officially endorsed the AST Division's plan for moving both projects forward in June 2023. In October 2023, MPS and AST presented both projects to the Facilities Readiness Panel, seeking approval to proceed to the Final Design phase; this decision is currently pending. These are laudable accomplishments that demonstrate AST's and MPS's continued commitment to begin addressing a cornerstone of Astro2020's recommendations.

Finding: The US has a strong legacy of astronomical discoveries using large optical-infrared dual-hemispheric telescopes (meaning one in the southern hemisphere and one in the northern hemisphere), which have been available to the US astronomy community since the mid-1990s. This has enabled US scientists to undertake a broad range of major survey programs, providing greater access, more instrumentation options, and the ability to follow up rare transients and other targets of opportunity regardless of their location in the sky. ELT access in both hemispheres would maximize support for discoveries from JWST and future space telescopes, Rubin, SKA, and ngVLA, and other emerging science cases.

Finding: Both the TMT and GMT consortiums have secured significant amounts of private funding towards their project costs. However, at present, neither has secured private funding at the level of 75% of the total project cost, which is the target level advanced by Astro2020, assuming both projects continue to move forward. A single US ELT with up to 50% public investment is an alternative funding scenario of Astro2020, which would necessitate a down-select between the two programs.

[17] https://www.nsf.gov/nsb/publications/2020/nsb202015.pdf

Finding: Absent other selection criteria beyond financial considerations, the US astronomical community and NSF, as the funding agency tasked with supporting the US ELT Program, face a very real challenge as program review matures to the decision point of construction. Construction costs to support the US ELT Program likely will require $1-3 B in public funds. This amount exceeds by a factor of two the largest investment by NSF in any capital project (Rubin/LSST, ~$500 M) prior to this point, and has little precedent based on historical funding levels of the MREFC account, which is driven by NSF-wide priorities as opposed to that of the AST Division.

Finding: Notwithstanding construction costs, which are very substantial in their own right, the costs that would be borne by AST to operate and manage (O&M) both observatories (typically 5-10% of the construction cost on an annualized basis, or of order $100 M/year), represent a significant portion (~30-35%) of the current AST budget, which is roughly $300M/year. Absent a permanent augmentation in funding for this purpose, very significant reductions or elimination of the individual grants program and/or other facility support in AST would be required. We note that Astro2020 also calls for a 50% increase in the AST individual investigator grant program, which is in direct conflict with this outcome.

Finding: The AST Division's current funding level is wholly insufficient to fully implement Astro2020.

Finding: In February 2024 the National Science Board (NSB) issued a statement and resolution regarding the US ELT Program[18]. The NSB indicated that they "stand ready to help the agency meet this important, ambitious, and visionary goal for U.S. science and leadership," and expressed concern "that the US ELT alone would require about 80% of the historical Major Research Equipment and Facilities Construction (MREFC) budget even under the *Astro2020*-recommended $1.6 billion investment." The NSB recommended that "the USELT Total Project Cost to NSF not exceed the $1.6 billion MREFC investment proposed by *Astro2020",* that "NSF discuss with the Board during the May 2024 meeting its plan to select which of the two candidate telescopes the Agency plans to continue to support", and that "NSF discuss with the Board during the May 2024 meeting its progress in developing a long-term agency strategy for MREFC projects."

Comment: The AAAC supports the US ELT Program and awaits the outcome of the May 2024 NSB meeting.

Finding: Unless or until the construction and O&M costs summarized above are addressed at the highest levels within NSF and in consultation with Congress and OMB, the US astronomical community runs the very real risk that the US ELT Program will not come to fruition, and, by default, US leadership in answering nearly every important science question across all three priority science areas of Astro2020 will be ceded to other nations. It should be emphasized that astronomical advances and discoveries are some of the most tangible and effective ways in which science connects with the public, captures their imagination, generates excitement and pride, and in turn, helps build broad public support for all science.

[18] https://www.nsf.gov/nsb/news/news_summ.jsp?cntn_id=309171

Finding: Research supported by AST and to a lesser extent PHY in the MPS Directorate is heavily dependent on the use of large, shared facilities; this model is less so in many other disciplines. For this reason, community input in the form of a decadal survey is central to developing consensus around the highest priority initiatives on a multi-year timescale. At present, AST devotes roughly 65% of its annual budget to O&M, PHY 30%, with the three other Divisions at the 10% level or below, even though all five Divisions have roughly the same annual budget (of order $300 M/year). As the cost to build new, world-class facilities has risen to the billion-dollar level with O&M costs northward of $100 M/year, the model of Division ownership is no longer sustainable, and one that adversely impacts AST and to a lesser extent PHY.

Recommendation: The AAAC recommends that NSF, in consultation with OMB, continue to explore agency-level ownership of the facility portfolio within MPS,[19] given the rising costs associated with the construction and operation of new world-class facilities, and, equally importantly, that these facilities have strategic importance on the national or agency-level, as opposed to that of a single scientific discipline or Division. If implemented, this change would enable the AST Division to support a vibrant individual investigator grants program and more focused research infrastructure specific to astronomy, while continuing to engage and support innovative cross-cutting initiatives with other Divisions.

Recommendation: The AAAC recommends that NSF proceed with all due deliberate speed toward a funding decision of the US ELT Program, consistent with internal review policies, and consistent with recommendations of Astro2020.

Recommendation: Consistent with recommendations from NSF's Facilities Readiness Panel and the National Science Board, the AAAC recommends that NSF and its senior leadership explore solutions for increased resources in their annual budget submissions in support of construction funding for the US ELT Program. We note that augmentation funding was provided in FY2023 and proposed in FY2024 for this purpose, suggesting strong and continued Congressional support for this Decadal priority.

2. CMB-S4, the Fourth-Generation Ground-Based Cosmic Microwave Background Experiment

The next-generation ground-based cosmic microwave background experiment, CMB-S4, is a project that has the support of both the astronomy and particle physics communities and requires coordination between and within funding agencies. CMB-S4 will transform our understanding of inflation in the early universe, light relic particles, measure distant galaxy clusters, and discover astronomical transients in the millimeter wave. The U.S. has been the worldwide leader in ground-based CMB observations, in part enabled by world-class capabilities for science at the NSF-run Amundsen Scott South Pole Station.

[19] https://www.nsf.gov/nsb/publications/2018/NSB-2018-17-Operations-and-Maintenance-Report-to-Congress.pdf

This field produces students who are trained in highly valued skills related to instrumentation and data analysis, including semiconductor fabrication and AI/ML.

CMB-S4 was first described in the 2014 Snowmass process and then endorsed by the following P5 report[20]. CMB-S4 was next identified as the second-highest priority ground-based facility of Astro2020 (along with ngVLA), with a recommendation that the NSF and DOE jointly pursue the design and implementation of this project.

Finding: Infrastructure resources at the South Pole, both current and planned, are of critical importance to realize the full scientific potential of the CMB-S4 project and future ones such as IceCube-Gen2, both of which are very high priorities to the astronomical and particle physics communities.

Finding: Given the challenges with infrastructure capacity at the South Pole, the CMB-S4 project completed an Analysis of Alternatives study in April 2023 at the request of the funding agencies. This year-long study successfully developed an alternative design that can meet all science goals while fitting within the existing infrastructure at the South Pole.

Finding: The recent 2023 P5 report[21] identified CMB-S4 as the highest priority new major project in particle physics, and preserved full funding for CMB-S4 without a reduction in scope in the considered funding scenarios.

Recommendation: Given that CMB-S4 is a high priority for the astronomy and particle physics communities and the current CMB-S4 design is compatible with the logistics constraints of the South Pole, the AAAC recommends that NSF-AST propose CMB-S4 for the Major Facilities Design Stage and schedule a Conceptual Design Review (CDR) as soon as possible and by the end of FY24.

Finding: Oversight and infrastructure planning at the South Pole falls under the purview of NSF-OPP, Division of Polar Programs, with the Arctic and Antarctic programs having separate sections. Furthermore, NSF-OPP resides in the Directorate for Geosciences (GEO), not the Directorate for Mathematical and Physical Science (MPS), where the AST Division is located.

Recommendation: Because OPP and AST operate in different administrative and management hierarchies within NSF, the AAAC echoes the recommendation of the P5 report for continued direct, close, and frequent coordination between the Antarctic section of NSF-OPP, NSF-AST, DOE, and the CMB-S4 project to ensure infrastructure planning is well aligned with the scientific needs of this project and future ones.

Recommendation: Consistent with the importance the AAAC places on sustainability, the AAAC Committee recommends that NSF-OPP continue to explore, and implement, if feasible, additional

[20] https://usparticlephysics.org/2014-p5-report/
[21] https://www.usparticlephysics.org/2023-p5-report/

renewable systems at both McMurdo station and the South Pole. A 2012 report of the US Antarctic Program Blue Ribbon Panel[22] concluded that McMurdo station could become completely energy-independent with the exception of transportation; although McMurdo is separated by roughly 850 miles from the South Pole, it serves as a very important staging area. A very recent analysis of renewable energy systems at the South Pole[23] suggests that various combinations of solar photovoltaics, wind turbine generators, lithium-ion energy storage, and long-duration energy storage could be immediately cost-effective given its extremely remote location.

3. Next-Generation Very Large Array

The Next-Generation Very Large Array (ngVLA), along with CMB-S4, is the second highest priority new ground-based facility recommendation of Astro2020. When fully constructed in the mid-2030s, the sensitivity and spatial resolution of this interferometric array is expected to exceed by more than an order of magnitude that of the Jansky VLA and ALMA at the same wavelengths. Current plans are for more than 250 ngVLA antennas to be deployed across roughly 10 US states and territories. Astro2020 calls for support to aid in the science design, development, cost studies, and antenna prototyping, with the NSF assessing the project's readiness, and proceeding with construction if the project is scientifically and financially viable, at the conclusion of this study.

Finding: In September 2023, the ngVLA entered NSF's Major Facility Design process at the Conceptual Design Phase, with a Conceptual Design Review (CDR) expected in Spring 2024. The NSF also awarded a 3-year, $21 million grant to advance the ngVLA design. An informational presentation on the project status was made to the National Science Board in November 2023. In totality, these are laudable developments that demonstrate the project's strong scientific and technical promise and NSF's continued commitment to U.S. leadership in radio astronomy.

Finding: In Sept. 2023, construction of the ngVLA prototype antenna, an 18 m dish, was completed following a design review in Dec. 2022. The prototype will be moved to the VLA site in New Mexico later in 2024 and undergo additional testing before integration into the current VLA.

Finding: As construction costs are estimated to be of order $2.5 B and operation costs in the range of $100M/year, the findings and recommendations related to the financial hurdles for the US ELT program apply to financing the ngVLA as well.

Recommendation: Consistent with the recommendation made for the ELT program, the AAAC recommends that NSF, in consultation with OMB, continue to explore agency-level ownership of the facility portfolio within MPS,[24] given the rising costs associated with the construction and operation of new world-class facilities.

[22] https://www.nsf.gov/geo/opp/usap_special_review/usap_brp/rpt/antarctica_07232012.pdf
[23] https://arxiv.org/abs/2306.13552
[24] https://www.nsf.gov/nsb/publications/2018/NSB-2018-17-Operations-and-Maintenance-Report-to-Congress.pdf

Recommendation: Additionally, the NSF and the ngLVA project should continue to actively pursue international, domestic (academic and industry), and multi-agency partnerships and cost-sharing agreements to address financial viability concerns given the very real budgetary constraints of NSF-AST, while still retaining the US as the majority stakeholder.

B. Space-Based Missions

Astro2020 recommended as its highest priority for NASA a ~6-meter space telescope that would survey nearby stars for habitable planets that can be studied for evidence of the presence of life and conduct a program of transformational astrophysics. This infrared/optical/ultraviolet observatory would directly image potentially habitable worlds outside our solar system, and, using spectroscopy, search for evidence of chemical biosignatures in the atmosphere of these planets. This mission would also provide new insights into how galaxies form and develop over time; it is expected to launch in the late 2030s or early 2040s. This proposed mission has a working title of "Habitable Worlds Observatory" (HWO).

The Astrophysics Probe is a new $1 B mission line recommended by Astro2020 to provide capabilities between MIDEX-class and flagships.

Finding: NASA's Astrophysics Division convened two working groups in 2023 to establish the fundamental science goals and technological needs for HWO. In September 2023, 56 individuals were selected to participate in two teams that will guide maturation activities: a Science, Technology, and Architecture Review Team (START) and a Technical Assessment Group (TAG). A kickoff meeting of both teams took place in late October 2023. Membership in a variety of Working Groups and Subgroups is now underway; each group is expected to closely engage with the broader science, technology, and engineering community in the course of their discussions and deliberations. Between 18 months and 3 years will likely be needed to deliver a final report to NASA with all relevant analyses and assessments.

Finding: NASA also completed its Announcement of Opportunity for the PI-led Astrophysics Probe Explorer in November 2023. This $1 B cost cap program solicited proposals for one of the two mission themes recommended by Astro2020: a far infrared mission and an X-ray probe, the latter to complement the European Space Agency's Athena mission. Selection of one or perhaps two mission concepts for competitive Phase A studies is expected in Fall 2024.

Finding: The cadence of the Explorer's program ($300 M cost cap) has been delayed 2 years; the status of the Pioneers program ($20M cost cap) is not yet clear.

Recommendation: NASA should continue to advance the HWO concept in a period of budget uncertainty while sustaining a robust science portfolio of other large missions. The AAAC specifically emphasizes the need for strong and continued support for the two remaining Great Observatories — Hubble and Chandra. Both continue to produce exceptional results in their extended phase of

operations and remain heavily oversubscribed. When the capabilities of these two flagships are viewed in the context of proposed US-led ground and space telescopes in the next decade and beyond, the most glaring gap is in the X-ray region, emphasizing the importance of maintaining the science capability Chandra provides as long as possible.

Finding: NASA's Tracking and Data Relay Satellite System (TDRSS) has provided essential communication and navigation services to NASA missions since 1983; 99% of mission data and data for navigating NASA missions in low-Earth orbit presently employ this system. In April 2022, NASA announced plans to develop commercial near-Earth space communication services that would replace TDRSS, with future missions prevented from including TDRSS in their mission planning. NASA contracted with six vendors to pursue communication services and is expected to select one or more of these vendors for near-Earth operations by 2030, followed by a phase-out of its own systems.

Finding: The proposed satcom systems are not dedicated to solely serving the needs of NASA and are expected to serve commercial customers, and therefore would likely be required to use commercial frequencies for space-to-space communications. However, existing frequency bands for fixed and mobile satellite services do not currently provide allocations for such a use case. As such, this change would have to be adopted at a future World Radiocommunication Conference (WRC). Given the cadence of this conference (3 to 4 tears) and that WRC-23 was held just a few months ago, timing and adoption/approval are concerns.

Finding: NASA commissioned a Science Analysis Group (SAG) to produce a report on TDAMM science requirements for communications in July 2023.

Recommendation: NASA should follow the recommendations of the SAG when selecting vendors for future communication services.

C. Other Topics

1. Astronomical Data Infrastructure

The astronomical community must embrace the opportunities and challenges associated with significantly increased volumes of data produced by astronomical telescopes, and downstream issues related to data archival management, access, and interoperability. Driven by this data revolution, Astro2020 recommended that NASA and NSF enhance coordination among US data archives and establish a central liaison for global archival interactions guided by astronomical research needs. Additionally, they advocate for NSF and relevant entities to formulate strategies for developing and maintaining software infrastructures across observatories, ensuring standardized archiving of observations for public use, supported by targeted funding.

Finding: TDAMM is one of many science cases requiring data across multiple archives. LSST, for example, is predicted to have a 200 Petabyte data archive at survey completion.

Finding: In 2023, NSF announced the Simonyi Scholars program to enhance AST funding for Rubin science and a call for the AI Institutes for the Astronomical Sciences to support astronomy through basic AI research, a program co-funded by the Simons Foundation.

Finding: The Center for Computational Astrophysics (CCA) at the Flatiron Institute, in collaboration with the National Science Foundation, arranged a "Future of Astrophysical Data Infrastructure Workshop" in February 2023. This workshop was structured to identify new strategies around implementing recommendations of Astro2020 that primarily relate to ground-based astrophysical data management. Their report, issued in November 2023,[25] made two high-level recommendations: (1) the formation of a Steering Committee that the agencies support to establish the most suitable structural model for addressing data and software infrastructure challenges; and (2) community engagement to assist in formulating an implementation plan for the relevant agencies.

Recommendation: The AAAC applauds the work and effort surrounding the Astrophysical Data Infrastructure Workshop and recommends that the agencies provide support to address the Workshop's two major recommendations. As this topic is relevant in nearly every area of science, there may be opportunities to engage in innovative cross-cutting initiatives and synergetic activities with a wide variety of stakeholders.

Comment: Effective data management encompasses a range of professional activities critical to ensuring data accuracy, security, and accessibility. For these reasons, it is imperative to establish career pathways for individuals who dedicate their efforts to pipeline, software, and archiving development.

Comment: Although there was somewhat greater focus in the Workshop report on ground-based facilities, many of the same issues are relevant and vital for NASA missions and DOE facilities.

Recommendation: As recommended in previous reports, the agencies and the AAAC should consider initiating a review of the 2014 Principles for Access to Large Federally Funded Astrophysics Projects and Facilities in light of the findings and recommendations from the 2023 Flatiron workshop.

2. Sustainability

Finding: NSF-AST has provided supplementary funds for its observatories and research centers to address climate change through the development of clean energy sources and technologies, reduction of energy usage, and enhancement of energy efficiency. With NSF funding support, NOIRLab aims to reduce its carbon footprint by 43% by late 2027 with a long-term goal of achieving carbon neutrality by 2040, largely by exploiting photovoltaic systems (solar panels).

[25] https://arxiv.org/pdf/2311.04272.pdf

Finding: NSF investments were used in the photovoltaic system upgrading of Gemini South Observatory on Cerro Pachón, NRAO Science Operations Center in Socorro, NM, and the Advanced Simons Observatory in the high Atacama Desert of Chile. Additional investments have been directed toward electric vehicle deployment in NSF's observatories. In Cerro Pachón, the installation of a large integrated photovoltaic (solar panel) and battery energy storage system is expected to meet all of the electricity needs from the Gemini South telescope, 50% of the needs from the International Gemini Observatory, and about 60% from the Vera C. Rubin Observatory once it becomes fully operational in late 2025.

Recommendation: The NSF should continue to fund additional energy efficiency projects to help its observatories and research centers achieve carbon neutrality.

Recommendation: NSF should share NOIRLab's successful experience and strategies in mitigating greenhouse gas emissions with other observatories and research centers of NSF and DOE. Such efforts serve as an exemplar of NSF's commitment to sustainability.

Comment: Across many sciences, data-intensive computing and data centers/storage are growing areas of energy consumption and carbon emissions.

Recommendation: Agencies should continue to pursue green computing practices. Doing so not only demonstrates environmental responsibility but also sets a standard for sustainable technology in the scientific community beyond the field of astronomy.