



Astrophysics Implementation Plan: 2018 Update

This Update summarizes events and developments since December 2016, that affect NASA's plans for achieving its strategic objectives in astrophysics and its progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*, including preparation for the 2020 Astrophysics Decadal Survey.

This Update is a supplement to the *Astrophysics Implementation Plan*, the *Astrophysics Implementation Plan: 2014 Update*, and the *Astrophysics Implementation Plan: 2016 Update*, which will not be revised.

**Astrophysics Division
Science Mission Directorate
NASA Headquarters**

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1. Introduction and Purpose

This Update summarizes events and developments since December 2016 that affect NASA's plans for achieving its strategic objectives in astrophysics and its progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*¹, including preparation for the 2020 Astrophysics Decadal Survey.

This Update is a supplement to the *Astrophysics Implementation Plan*², the *Astrophysics Implementation Plan: 2014 Update*³, and the *Astrophysics Implementation Plan: 2016 Update*⁴, which will not be revised.

¹ *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010), <https://www.nap.edu/download/12951>.

² *Astrophysics Implementation Plan* (NASA, December 2012), <http://science.nasa.gov/astrophysics/documents>.

³ *Astrophysics Implementation Plan: 2014 Update* (NASA, December 2014), <http://science.nasa.gov/astrophysics/documents/>.

⁴ *Astrophysics Implementation Plan: 2016 Update* (NASA, December 2016), <http://science.nasa.gov/astrophysics/documents>.

2. Summary of Changes since December 2016

NASA continues to make substantial progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*. As recognized by the 2016 Midterm Assessment, *New Worlds, New Horizons: A Midterm Assessment*⁵, (see Section 3 in the *Astrophysics Implementation Plan: 2016 Update*), the NASA astrophysics portfolio is well balanced and contains a mix of large-, medium-, and small-scale activities. Some of the important accomplishments since 2016 are listed here and described in more detail in subsequent sections.

- The James Webb Space Telescope has been assembled into two elements, the payload element and the spacecraft element. The payload element has successfully concluded its integration and test phase, including environmental testing at Goddard Space Flight Center and cryogenic testing at Johnson Space Center; testing of the spacecraft element is currently underway. The spacecraft element experienced delays related to integration and testing in 2017 and early 2018. NASA established a new launch date of March 2021. (Section 3)
- NASA completed an independent technical, management, and cost assessment of the Wide Field Infrared Survey Telescope (WFIRST). In response to this, NASA made several changes to the implementation of WFIRST; the net result is a total cost estimate of the mission to NASA's Science Mission Directorate of \$3.2B, excluding contributions and Headquarters-held reserves. The President's Budget Request for Fiscal Year (FY) 2019, released in February 2018, proposed to terminate WFIRST. Funds appropriated by Congress in FY 2018 allowed WFIRST to enter Phase B, and the project continues to make planned progress. Continuation of WFIRST through FY 2019 depends on the outcome of the FY 2019 appropriations process. (Section 4.1)
- In response to the Midterm Assessment, NASA increased its roles in ESA's Laser Interferometer Space Antenna (LISA) mission. NASA is working closely with ESA to support the mission trade and industrial studies during ESA's Phase A. (Section 4.2)
- NASA's involvement in ESA's Athena mission continues with NASA supporting studies and technology development during ESA's Phase A for contributions to both of Athena's instruments. (Section 4.3)
- One Small Explorer, the Imaging X-ray Polarimetry Explorer (IXPE), and one Mission of Opportunity, the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO), were downselected in January 2017 into development for flight. (Section 5.2)
- Three Medium Explorer (MIDEX) proposals and three Mission of Opportunity proposals were selected in response to the September 2016 Announcement of Opportunity and are now conducting competitive Phase A mission concept studies. A new Announcement of Opportunity for Small Explorers (SMEX) and Missions of Opportunity will be issued in Spring 2019. (Section 5.1)

⁵ *New Worlds, New Horizons: A Midterm Assessment* (NRC, 2016), <https://www.nap.edu/catalog/23560/new-worlds-new-horizons-a-midterm-assessment>.

- The Division continues to maintain a balanced program in Research and Analysis, where a new CubeSat element was added in FY 2019. (Section 6.3)
- The Stratospheric Observatory for Infrared Astronomy (SOFIA) will complete its 5-year prime mission in Fall 2019. NASA has been instructed by Congress not to include SOFIA in the 2019 Senior Review. Instead, NASA has initiated two independent reviews of SOFIA, one of its science progress and science prospects, and one of its operations and maintenance efficiency. (Section 7.1)
- The original Sensor Chip Electronics (SCE) being provided by NASA for ESA's Euclid mission developed thermomechanical problems and required a redesign. The redesign is complete, and production of new SCEs has started. They will be delivered to ESA during 2019. (Section 7.2)
- The JAXA-led X-ray Astronomy Recovery Mission, renamed X-ray Imaging and Spectroscopy Mission (XRISM), was formally approved as a project by both JAXA and NASA. (Section 7.3)
- Astrophysics had several successful launches: the Neutron star Interior Composition Explorer (NICER) in June 2017, the Cosmic Ray Energetics and Mass experiment (CREAM) in August 2017 (both to the ISS), and the Transiting Exoplanet Survey Satellite (TESS) in April 2018. (Section 8)
- The next Astrophysics Senior Review of operating missions will be held in Spring 2019. (Section 8.4)
- NASA continues to support the community's preparations for the 2020 Decadal Survey, including concept studies for large- and medium-scale missions, to be submitted to the Decadal Survey in Summer 2019. (Section 9)

NASA receives community advice from Federal Advisory Committees and from the Space Studies Board (SSB) of the National Academies. In January 2017, NASA chartered the Astrophysics Advisory Committee (APAC)⁶ to advise the Director of NASA's Astrophysics Division on NASA's astrophysics programs, policies, plans, and priorities. The APAC replaces the Astrophysics Subcommittee, which was a subcommittee of the Science Committee of the NASA Advisory Council (NAC). NASA continues to receive advice regarding its astrophysics programs from the Astronomy and Astrophysics Advisory Committee (AAAC)⁷ and the National Academies' Committee on Astronomy and Astrophysics (CAA)⁸.

⁶ APAC homepage at <https://science.nasa.gov/researchers/nac/science-advisory-committees/apac/>.

⁷ AAAC homepage at <https://www.nsf.gov/mps/ast/aaac.jsp>.

⁸ CAA homepage at http://sites.nationalacademies.org/bpa/bpa_048755.

Decadal Survey Recommendation	NASA Actions
Large-scale 1: WFIRST	Entered Phase B in 2018; no funding included in FY 2019 budget request (Section 4.1)
Large-Scale 2: Augmentation to Explorer Program	Executing four Announcements of Opportunity (AOs) per decade: (MIDEX 2011, SMEX 2014, MIDEX 2016, SMEX 2019, MIDEX 2021, etc.) (Section 5.1)
Large-Scale 3: LISA	Partnering on ESA's LISA gravitational wave observatory (Section 4.2)
Large-Scale 4: IXO	Partnering on ESA's Athena X-ray observatory (see Section 4.3)
Medium-Scale 1: New Worlds Technology Development Program	WFIRST coronagraph at TRL-6, starshade / coronagraph / stable segmented telescope technology development, EPDS, LBTI (Section 6.1)
Medium-Scale 2: Inflation Probe Technology Development Program	Balloon-borne technology experiments, detector investments (Section 6.2)
Small-Scale: Research Program Augmentations	R&A up 61 percent from FY 2010 to FY 2023; added TCAN (Section 6.3)
Small-scale: Intermediate Technology Development Augmentation	Initiated SAT program, includes competed and directed technologies
Small-Scale: Suborbital Program Augmentation	Added New Zealand campaigns, offering super-pressure balloon (Section 6.4), added CubeSats
Small-Scale: SPICA (U.S. contribution)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity (MO)

Table 1. Recommended space activities of the 2010 Decadal Survey supported by the FY 2018 NASA Appropriation, the FY 2019 President's Budget Request, and its notional out years.

3. James Webb Space Telescope

The James Webb Space Telescope⁹ has been assembled into two elements, the payload element, consisting of the combined telescope and science instruments, and the spacecraft element, consisting of the spacecraft bus and the sunshield. Once each of the elements has been fully integrated and tested, they will be combined to create the Webb observatory. The payload element has successfully concluded its integration and test phase, including environmental testing at the Goddard Space Flight Center (GSFC) and cryogenic testing at the Johnson Space Center (JSC). The science payload met its demanding requirements for sensitivity and image quality. The payload element was delivered to the Northrop Grumman Space Park facility where the completed spacecraft element also resides.

The spacecraft element experienced delays related to integration and testing in 2017 and early 2018. In response, the agency convened review boards, both internal and external, to evaluate the remaining activities and schedule. Following these reviews, NASA established a new launch date of March 2021¹⁰.

The spacecraft element resumed its environmental test program in late 2018 and integration with the science payload will occur in late 2019. Following that integration, the completed observatory will undergo its environmental test program before shipping to French Guiana in late 2020. Additionally, the mission operations center at the Space Telescope Science Institute (STScI) has been completed and is ready to support the launch, commissioning, and operations of Webb.

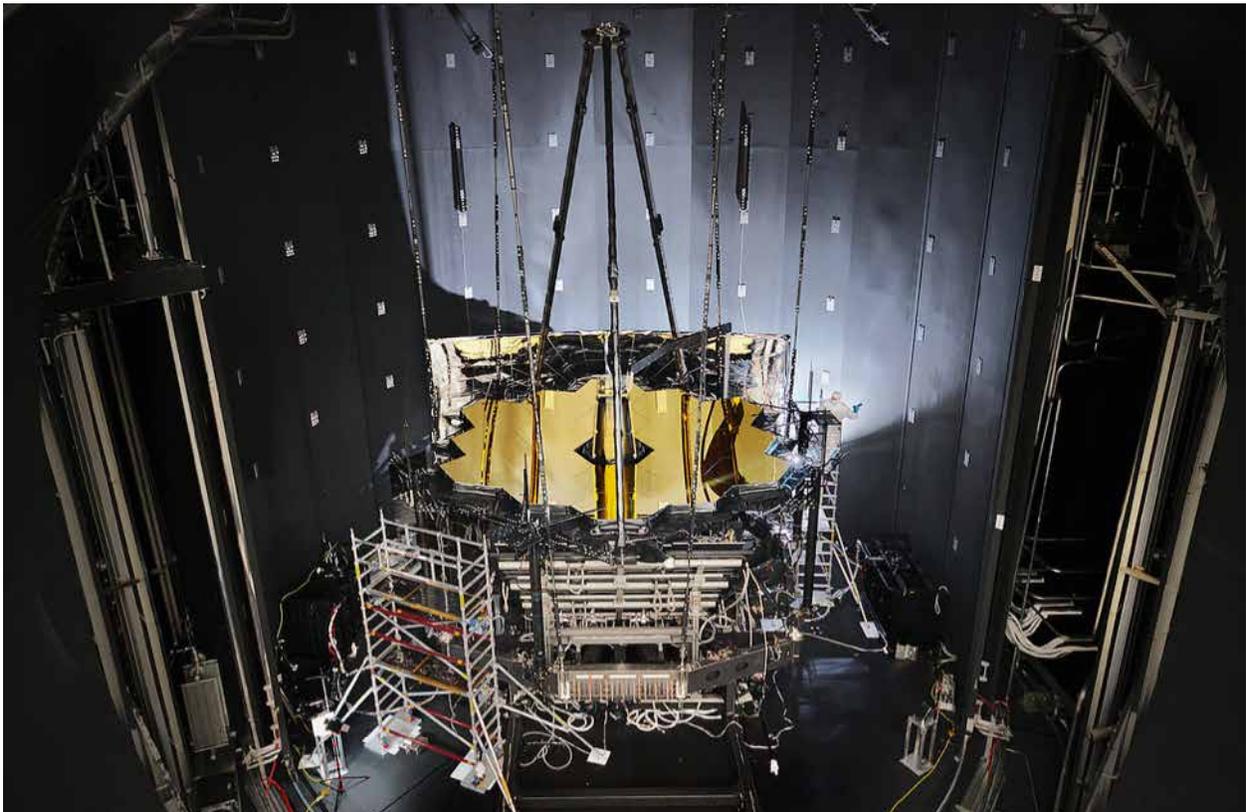


Figure 1. James Webb Space Telescope payload element, the combined telescope and science instruments, in the cryogenic test chamber at the Johnson Space Center.

⁹ Webb mission homepage at <https://www.jwst.nasa.gov/>.

¹⁰ Report of the Webb Independent Review Board (WIRB) and NASA response at <https://www.nasa.gov/press-release/nasa-completes-webb-telescope-review-commits-to-launch-in-early-2021>.



Figure 2. James Webb Space Telescope elements in the clean room at Northrup Grumman Space Park, including the spacecraft element (far left) and payload element (top center).

4. Large Scale Decadal Survey Priorities

4.1 Wide-Field Infrared Survey Telescope

The Wide Field Infrared Survey Telescope (WFIRST)¹¹ is the top-ranked large space mission in the 2010 Decadal Survey. WFIRST will provide definitive surveys to address the history of cosmic expansion and the growth of structure, the demographics of exoplanets, and statistical studies of the Milky Way and other galaxies in the near-infrared. WFIRST is designed to perform wide field imaging and surveys of the near infrared sky using an existing 2.4m telescope, the same size as the Hubble Space Telescope. The Wide Field Instrument provides a field of view 100 times larger than images provided by Hubble. The technology demonstration Coronagraph Instrument will pave the way for the detection and characterization of planets in other solar systems.

WFIRST held a successful Key Decision Point A (KDP-A) review in February 2016, formally progressing from a study to Phase A of an official NASA project. Since then, the project has made excellent technical progress. The milestone of Technology Readiness Level (TRL) 6 (prototyping demonstration in a relevant end-to-end environment) on the detectors was achieved in January 2017, over 2 years in advance of when this level of maturity is required by NASA standards.

The Midterm Assessment recommended that “Prior to KDP-B, NASA should commission an independent technical, management, and cost assessment of WFIRST.” As the project neared completion of Phase A in mid-2017, NASA’s Science Mission Directorate commissioned a special review, the WFIRST Independent External Technical/Management/Cost Review (WIETR)¹², held between June and October of that year. In addition to the positive findings related to the scientific value of the mission, the expertise of the team, and the maturity of the concept, the WIETR report found that the “lifecycle cost and ... budget profile ... are inconsistent with the scope, requirements, and the appropriate risk classification for the mission.”

In response to this, NASA made changes to the implementation of WFIRST:

- The Coronagraph Instrument is treated as a pure technology demonstration instrument, and the cost is shared with NASA’s Space Technology Mission Directorate.
- The Integral Field Channel is eliminated from the Wide Field Instrument.
- A simplified observatory design reduces complexity and eliminates unneeded mechanisms and features.
- Specific contributions to the mission by international partners are incorporated.
- An improved budget profile and accelerated schedule advances launch by 6 months.
- The development plan includes added measures to reduce mission risk (sparing, testing, parts, etc.).

In addition, NASA has clarified roles, accountability, and authority by re-assigning WFIRST to the newly created Astrophysics Strategic Missions Program at NASA Headquarters. The net result is a mission with an estimated total cost to NASA’s Science Mission Directorate of \$3.2B, excluding contributions and Headquarters-held reserves.

¹¹ WFIRST mission homepage at <https://wfirst.gsfc.nasa.gov/>.

¹² WIETR <https://www.nasa.gov/feature/nasa-receives-findings-from-wfirst-independent-review-team>.

The project completed a successful mission-level System Requirements Review (SRR) and Mission Definition Review (MDR) in February 2018. NASA approved WFIRST to proceed to Phase B following a successful Key Decision Point B (KDP-B) review in May 2018.

The President’s Budget Request for FY 2019, released in February 2018, proposed to terminate WFIRST: “Given competing priorities at NASA, and budget constraints, developing another large space telescope immediately after completing the \$8.8 billion James Webb Space Telescope is not a priority for the Administration. The Budget proposes to terminate WFIRST and redirect existing funds to other priorities of the science community, including competed astrophysics missions and research.” Funds appropriated by Congress in FY 2018 allowed WFIRST to enter Phase B, and the project continues to make progress on WFIRST according to the plan and budget approved during the KDP-B review. Continuation of WFIRST through FY 2019 depends on the outcome of the FY 2019 appropriation process.

Pending the FY 2019 appropriation, WFIRST will be working toward a Preliminary Design Review (PDR) in Fall 2019. The project has completed System Requirements Reviews for all major system elements, and has established contracts with Ball Aerospace for the Wide Field Instrument, Teledyne Scientific & Imaging for infrared detectors, and Harris Corporation for the telescope. NASA is engaging with the community to ensure that the investigations planned for WFIRST will address the most compelling science questions using the most current techniques during its operational lifetime.

Figure 3 shows a timeline for WFIRST with preliminary planning dates for major lifecycle events. Figure 4 shows the configuration of the observatory in mid-2018.

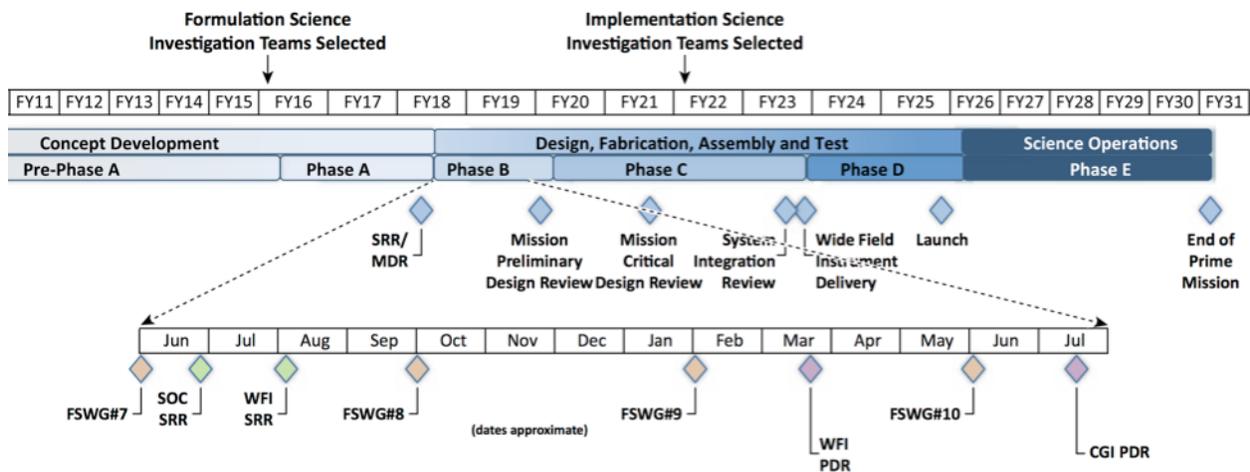


Figure 3. Preliminary timeline for the WFIRST mission highlighting major events in the project lifecycle. All dates are notional, but illustrate the sequence of events referred to in the text.



Figure 4. Mid-2018 design of WFIRST (left) and a full-size mockup without the outer barrel assembly (right), illustrating the scale of the observatory.

On the current schedule, WFIRST is expected to go through its confirmation review (KDP-C) in late 2019 or early 2020, during the conduct of the 2020 Decadal Survey. Thus, the Decadal Survey Statement of Task (see Section 9.1) does not require that WFIRST be ranked with missions recommended for the next decade, but it does ask the Decadal Survey Committee to assess whether WFIRST plays an appropriate role in the research strategy for the next decade.

4.2 Laser Interferometer Space Antenna

In June 2017, the European Space Agency’s (ESA) Science Programme Committee selected the Laser Interferometer Space Antenna (LISA)¹³ proposal as its mission to address the science of the gravitational universe, with anticipated launch in the 2030s. ESA conducted trade studies for the mission payload instruments during its Phase 0, which ran from September 2017 through April 2018, and which included significant U.S. involvement. ESA’s Phase A started in May 2018 and will lead to Mission Confirmation Review (MCR) in February 2019. Mission Adoption is expected in 2022.

In response to the Midterm Assessment, NASA has increased its planned contribution to the LISA mission. NASA is studying a contribution of payload instrumentation, additional hardware for the mission, and science and ground-based activities. U.S. scientists and engineers are currently working closely with ESA’s System Engineering Office in trade studies and mission performance assessments, as well as with the LISA Consortium in science and data analysis activities.

The NASA LISA Study Office, established in 2016 within the Physics of the Cosmos (PCOS) Program Office at GSFC, is managing NASA investments in five core LISA technologies (telescope, lasers, charge management system, micro-thrusters, and phasemeter), which are candidates for U.S. contribution to the LISA payload. Through the Study Office, U.S. technologists and scientists participate and contribute to the Phase A activities of ESA’s Systems Engineering Office. NASA plans to establish a LISA project at GSFC in 2019.

¹³ NASA LISA mission homepage at <https://www.lisa.nasa.gov/>.

In Summer 2017, NASA established the NASA LISA Study Team (NLST)¹⁴, replacing the NASA L3 Study Team, to conduct studies for U.S. technology and science contributions to the mission. The NLST will write a report for the 2020 Decadal Survey committee, presenting the science case for U.S. involvement in LISA. The NLST is also looking at the requirements of the U.S. astrophysics community to ensure optimal scientific return from LISA.

In Summer 2018, ESA established the LISA Science Study Team (SST), whose primary task is to provide guidance to ESA on scientific issues as the mission architecture is being developed. NASA nominated three members of the U.S. astrophysics community as full members of ESA's LISA SST.

To prepare the U.S. community for LISA science and to support collaboration with the working groups of the LISA Consortium¹⁵, in February 2018 NASA issued the LISA Preparatory Science (LPS) solicitation as part of ROSES-2018. The LPS program supports U.S. investigators developing tools for LISA data analysis and conducting astrophysics investigations that pave the way toward better understanding of the LISA data. Selections were made in November 2018.

The selected teams will provide a status report at a special session of the Winter 2020 AAS meeting.

4.3 Athena X-ray Observatory

At ESA, Athena is currently in an extended Phase A, with Phase A2 beginning in Fall 2018 and ending in Summer 2019. ESA plans to formalize the instrument consortia for the two instruments, the X-ray Integral Field Unit (X-IFU) led by France and the Wide Field Instrument led by Germany, in early 2019. Adoption of the Athena mission is planned for 2021. Launch is planned for 2031 to either Sun-Earth L1 or L2, with a decision in 2019.

The NASA Athena Study Office¹⁶, established in 2016 within the PCOS Program Office at GSFC, is managing NASA's studies of potential contributions to the Athena mission. NASA plans to establish an Athena project at GSFC in 2019.

NASA is supporting study efforts for potential hardware contributions to both of Athena's science instruments. A team led by GSFC will provide the microcalorimeter sensor unit for the X-IFU Demonstration Module in 2019 and is studying provision of the flight microcalorimeter sensor unit. A team led by Pennsylvania State University is studying the provision of a Wide Field Instrument Science Products Module and Application Specific Integrated Circuit (ASIC) design, as well as heat pipes. NASA and ESA continue discussions on possible additional NASA contributions to Athena.

ESA's Athena Science Study Team (SST) has established an Athena Science Working Group (SWG) structure populated by members of the European and U.S. community¹⁷. There are more than 100 U.S. members of Athena SWGs. U.S. membership in the Athena SWGs continues to grow. As part of its non-hardware contribution to the Athena mission, NASA plans to fund U.S. members of the Athena science team, a U.S. science data center, and U.S. general observers during mission operation.

¹⁴ NASA LISA Study Team homepage at <https://lisa.nasa.gov/L3Study.html>.

¹⁵ LISA consortium homepage at <https://www.elisascience.org/>.

¹⁶ NASA Athena study homepage at <https://pcos.gsfc.nasa.gov/studies/athena/>.

¹⁷ Athena science community homepage at <https://www.the-athena-x-ray-observatory.eu>.

5. Astrophysics Explorers Program

5.1 Announcements of Opportunity

The two Explorer missions that were downselected in Spring 2013 and confirmed for implementation in 2014, the Transiting Exoplanet Survey Satellite (TESS) – a Medium-class Explorer (MIDEX) – and the Neutron star Interior Composition Explorer (NICER) – a Mission of Opportunity (MO) – were launched in April 2018 and June 2017 respectively (Sections 8.1 and 8.2).

The Astrophysics Explorers Program Announcements of Opportunity (AOs)¹⁸ that were released in September 2014 for Small class Explorers (SMEX) and MO proposals resulted in the 2015 selection of three SMEX mission concepts and two MO mission concepts for Phase A Concept Studies. The concept study reports were submitted to NASA in July 2016 and were evaluated over the ensuing several months. The Imaging X-ray Polarimetry Explorer (IXPE) SMEX mission was downselected in January 2017, and the Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO), an MO to be launched on an Ultra Long Duration Balloon (ULDB), was downselected in Spring 2017. Both missions continue their implementation towards launch (Sections 5.2.1 and 5.2.2).

AOs¹⁹ for MIDEX and MO proposals were released in September 2016, and led to the 2017 selection of three MIDEXes and three MOs for nine-month Phase A Concept Studies²⁰. The concept study reports were submitted to NASA in May 2018, and downselection for flight is expected in early 2019.

In November 2018, a draft AO²¹ was released for SMEX and MO proposals. The 2019 SMEX and MO AO is planned for Spring 2019, with proposals due in Summer 2019. Subsequent AOs, each for a mission and a MO, are anticipated every 2-3 years.

5.2 Explorers Missions in Development:

5.2.1 *Imaging X-ray Polarimetry Explorer*

The Imaging X-ray Polarimetry Explorer (IXPE)²² was downselected in February 2017. IXPE will exploit the polarization state of X-rays from astrophysical sources to increase our understanding of extreme cosmic sources. During IXPE's two-year mission, it will study targets such as active galactic nuclei, quasars, pulsars, pulsar wind nebulae, magnetars, accreting X-ray binaries, supernova remnants, and the Galactic center. IXPE consists of three identical imaging X-ray polarimetry systems mounted on a common optical bench. IXPE plans to launch in 2021. The mission is an international collaboration with hardware and science team contributions from Italy and Japan.

During 2018, the Marshall Space Flight Center (MSFC) has been fabricating the engineering model X-ray mirrors, the Italian collaborators have passed the Critical Design Review (CDR) on the X ray detector units, and the Japanese collaborators have delivered two engineering model heat shields. IXPE passed its confirmation review (KDP-C) and began Phase C in November 2018.

¹⁸ 2014 Astrophysics Explorers AO acquisition page at <https://explorers.larc.nasa.gov/APSMEX/>.

¹⁹ 2016 Astrophysics Explorers AO acquisition page at <https://explorers.larc.nasa.gov/APMIDEX2016/>.

²⁰ <https://www.nasa.gov/press-release/nasa-selects-proposals-to-study-galaxies-stars-planets>

²¹ 2019 Astrophysics Explorers AO acquisition page at <https://explorers.larc.nasa.gov/2019APSMEX/>.

²² IXPE mission homepage at <https://ixpe.msfc.nasa.gov/>.

5.2.2 Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory

The Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory (GUSTO) is a balloon-borne Explorers mission under development. The GUSTO payload is a 1-meter class telescope with terahertz heterodyne detectors that will perform large-scale surveys and spectral diagnostics of the interstellar medium in our Milky Way and the Large Magellanic Cloud to answer key questions about the life cycle of the interstellar medium and massive star formation. The observation will be performed during an Ultra-Long Duration Balloon (ULDB) super-pressure balloon flight from Antarctica of up to 100 days in duration with a scheduled launch in December 2021. During November 2018, GUSTO completed its mission-level Preliminary Design Review in preparation for a confirmation review (KDP-C) in early 2019.

6. Medium- and Small-Scale Decadal Survey Priorities

6.1 New Worlds Technology Development

The 2010 Decadal Survey recommended that candidate starlight suppression techniques be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade. NASA has been developing new technology to enable exoplanet imaging and spectroscopy missions through competitively selected individual investigator awards issued under the Astrophysics Research and Analysis (APRA) and Strategic Astrophysics Technology (SAT) programs. To date, more than 35 awards have been made for tasks that advance the technology readiness of external occulters (starshades), coronagraphs, and their associated supporting technologies. A directed technology development program was established in 2013 to mature the technology required for the WFIRST coronagraph instrument (CGI). The final technology development milestone was achieved in 2017; in 2018, CGI entered the preliminary design phase as a flight technology demonstration instrument. In 2016, NASA established the S5 (“starshade to TRL-5”) starshade technology development activity with the goal of advancing starshade technology for consideration by the 2020 Decadal Survey. In 2018, approval was given for the S5 technology development activity to enter the implementation phase.

Initial studies of future exoplanet imaging and spectroscopy missions have concluded that new technologies will be required to enable the large, ultrastable telescopes required for such missions. In late 2017, NASA initiated a technology development program specifically designed to mature the integrated system architectures that will enable the next generation of large space telescopes. NASA solicited industry proposals to carry out one-year end-to-end system-level engineering design and modeling studies and associated testbed demonstrations of large (10 meter class or larger) segmented-aperture telescopes with integrated coronagraphs that will lead to the identification of priority technology investments and subsequent support to start developing and maturing these technologies. In early 2018, after an open call for proposals, two industry teams were selected. These teams are conducting 12-month system-level engineering studies for large mission concept studies that require precise, stable, segmented opto-mechanical systems to enable the large apertures required to achieve their scientific objectives. A follow-up, multi-year program of technology development is planned.

The 2010 Decadal Survey recommended that NASA and NSF should support an aggressive program of ground-based high-precision radial velocity surveys of nearby stars to identify potential candidates for a future space-based imaging and spectroscopy mission. NASA has partnered with NSF to provide capabilities for the community to conduct high precision radial velocity surveys using the 3.5-m WIYN telescope on Kitt Peak. NASA is developing the NEID²³ extreme precision Doppler spectrometer (EPDS) to be installed as a facility-class instrument on the WIYN telescope; NEID is scheduled for commissioning in Fall 2019.

The 2010 Decadal Survey identified the need to quantify the characteristic levels of exozodiacal dust about potential exoplanet host stars. To address this need, NASA developed the Large

²³ NEID stands for “NN-EXPLORE Exoplanet Investigations with Doppler spectroscopy;” the NEID team homepage is at <https://neid.psu.edu/>.

Binocular Telescope Interferometer (LBTI)²⁴ and invested in the associated survey of exozodiacal dust levels around a set of nearby stars. In 2018, the survey completed after observations of 38 stars with data delivered to the public archive.

NASA is supporting precursor science activities necessary for a future exoplanet-imaging mission through the Exoplanet Research Program (XRP) and the Nexus for Exoplanet System Science (NExSS)²⁵, a NASA research coordination network dedicated to the study of planetary habitability.

6.2 Inflation Probe Technology Development

NASA continues to support two Cosmic Microwave Background (CMB) polarization balloon projects: SPIDER²⁶ and PIPER²⁷. SPIDER had its first science flight launch in January 2015, and PIPER had its first engineering flight in October 2017. SPIDER will be flown for its second science flight from McMurdo Station, Antarctica, in the campaign beginning December 2018, weather permitting; PIPER has four science flights planned for each of March and September 2019 and 2020. If successful, initial results are expected to be published within the next several years from these two independent teams.

NASA supports CMB polarization technology development, particularly those that exploit superconducting detectors, through the APRA and SAT programs. NASA is supporting novel approaches in detectors, polarized input coupling methods, multiplexing readouts, and millimeter-wavelength coatings and filters. The state-of-the-art for the critical focal plane array technologies is for near photon-noise-limited detector arrays with thousands of elements, which have been fabricated for testing and use in CMB polarization balloon projects and ground-based projects as technology readiness demonstrators for a possible future Inflation Probe mission. In addition, data reduction and analysis techniques are also being developed and tested via these projects. NASA is also supporting technology development through the Explorers Program for a potential MO to provide detectors for the JAXA LiteBIRD mission.

6.3 Research and Analysis

The Astrophysics Division continues to execute a balanced Research and Analysis (R&A) program. R&A support saw a 26 percent funding increase since the 2010 Decadal Survey (FY 2010–FY 2018) in response to Decadal Survey priorities and recommendations, resulting in selection rates of >20 percent across the entire R&A program. An additional projected 28 percent increase in R&A support planned over the next five years (FY 2019 President’s Budget Request and FY 2020–FY 2023 notional planning) will further increase selection rates (Figure 5).

²⁴ LBTI page of the NASA Exoplanet Science Institute at <http://nexsci.caltech.edu/missions/LBTI/>.

²⁵ NExSS homepage at <https://nexss.info/>.

²⁶ SPIDER used to be an acronym, but now is the project’s formal name; the SPIDER team homepage is at <https://spider.princeton.edu/>.

²⁷ PIPER stands for “Primordial Inflation Polarization Explorer;” the PIPER team homepage is at <https://asd.gsfc.nasa.gov/piper/>.

Planned Growth in R&A Funding

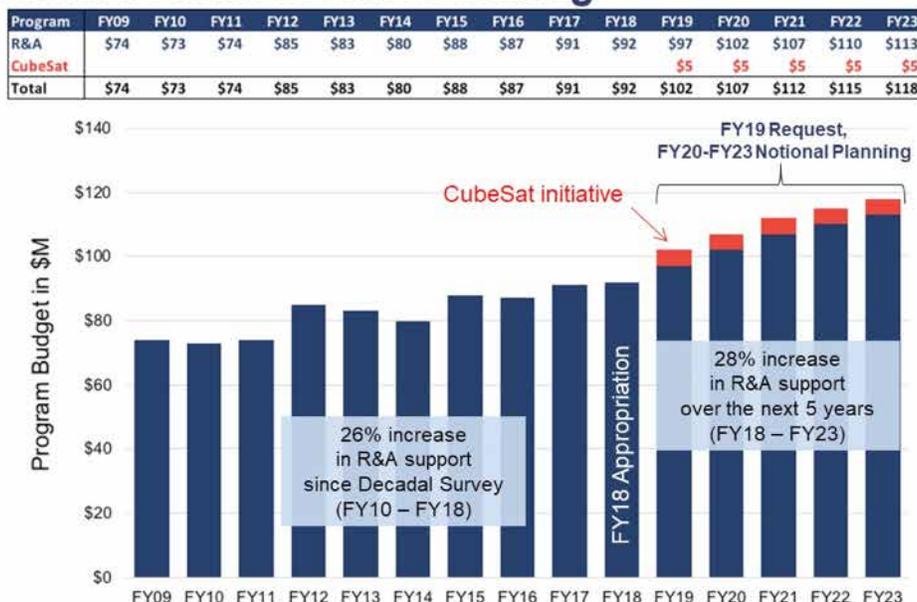


Figure 5. Realized and planned growth in the Research and Analysis (R&A) program budget since the 2010 Decadal Survey.

The 2010 Decadal Survey recommended establishing Theory and Computational Astrophysics Networks (TCAN). Following the completion of the first six TCANs, which were funded in partnership with NSF, three second-cycle networks were selected in 2018 for funding by NASA alone.

The Astrophysics Division is implementing a CubeSat initiative that adds \$5M to the R&A budget annually starting in FY 2019. Astrophysics CubeSats are solicited through the Astrophysics Research and Analysis (APRA) program element, and five Astrophysics CubeSats have been selected over the past four years. The first Astrophysics CubeSat selected through the R&A program (HaloSat²⁸, to study the hot interstellar medium) was deployed from the International Space Station (ISS) in July 2018. The \$5M annual funding for CubeSats will allow a sustained selection averaging at least one new CubeSat per year over the coming years.

Astrophysics SmallSats, with an emphasis on those that can be launched on an EELV Secondary Payload Adapter (ESPA) ring, will be solicited as small Missions of Opportunity through future Astrophysics Explorers AOs. In order to prepare the community for this flight opportunity, first being offered in 2019, NASA solicited proposals for Astrophysics SmallSat mission concept studies in 2018. Nine mission concept proposals were selected²⁹ in Summer 2018 for funding.

6.4 Technology Development

The Astrophysics Division has executed an aggressive technology development program during this decade. The technology development investments have been both strategic and tactical in nature with several distinct elements.

²⁸ HaloSat team homepage at <http://halosat.physics.uiowa.edu/>.

²⁹ Announcement of Astrophysics SmallSat mission concept studies at <https://www.nasa.gov/feature/nasa-astrophysics-eyes-big-science-with-small-satellites>.

The core of the astrophysics technology development program is the Astrophysics Research and Analysis (APRA) program element, which supports basic research and technology initiation with development up to TRL 3 in the lab and TRL 9 for suborbital missions. Mid-TRL technology development is supported in the Strategic Astrophysics Technology (SAT) program element. At the beginning of the 2010s decade, SAT was focused at the technologies required to realize those missions identified in the 2010 Decadal Survey. Once we identified the four mission concepts that would be studied for the 2020 Decadal Survey, enabling technologies for those missions were also prioritized. Focused technology development is critical for realizing our strategic missions, such as WFIRST. The enabling technologies for WFIRST, the next generation detectors for the Wide Field Instrument and the multiple technologies for the Coronagraph Technology Demonstration Instrument, have been invested in since FY 2014.

Figure 6 shows the technology investments that NASA Astrophysics have made during the decade; more than \$600M has been invested in technology development by NASA Astrophysics during FY 2013—FY 2019. The 2010 Decadal Survey prioritized technology development in several areas, including direct imaging of exoplanets (Section 6.1), detection of cosmic microwave background polarization (Section 6.2), and others.

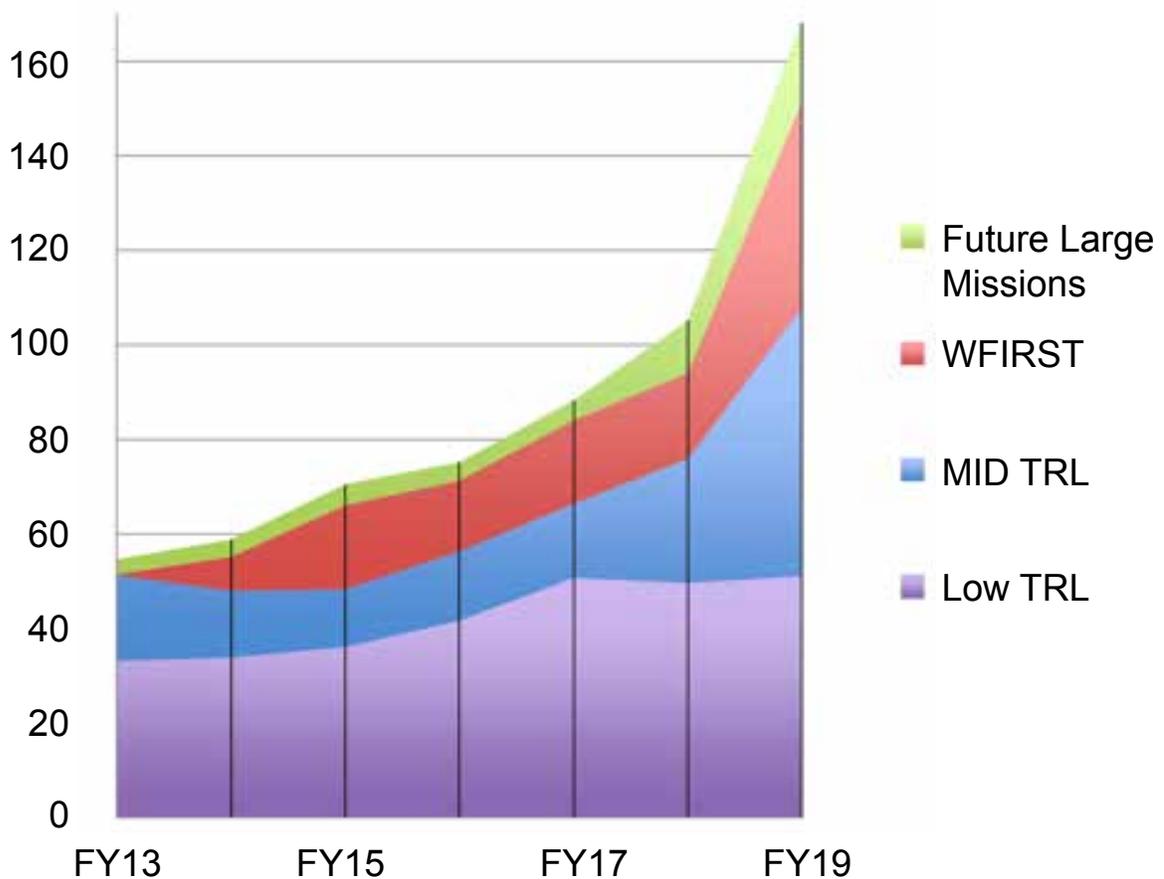


Figure 6. Investments in astrophysics technology development from FY 2013—FY 2019.

6.5 Scientific Balloon Program

The NASA Balloon Program³⁰ continues to increase the capabilities available to the scientific community for PI-led suborbital missions. Annual campaigns of conventional (1 day or less) balloon flights are offered from Palestine TX and Ft. Sumner NM. The annual NASA long-duration balloon (LDB) campaign from McMurdo Station, Antarctica, with logistical support from NSF, provides up to three balloon launches with multi-circumnavigation orbits of the South Pole yielding up to 55 days aloft in a single flight. Advances have been made toward qualifying a super-pressure balloon (SPB), with the capability to maintain altitude through repeated diurnal cycles while supporting a payload of up to 1 ton at an altitude of up to 33.5 km (20.8 miles). This capability in turn allows for extended balloon-borne astronomical observation at mid-latitudes through repeated day-night cycles. To this end, the Balloon Program has established a launch capability in Wanaka, New Zealand, which allows southern-hemispheric launches of super-pressure balloons with payload recovery in South America. Two payloads have been launched from Wanaka during the SPB qualification program on a shared risk basis. NASA also offers multi-day conventional balloon flights from Sweden to Canada.

Payloads for NASA's scientific balloon program, as well as NASA's sounding rocket payload, are supported through the APRA research program element, which has annual solicitations.

³⁰ Scientific balloon project homepage at <https://sites.wff.nasa.gov/code820/>.

7. Other Astrophysics Missions

7.1 Stratospheric Observatory for Infrared Astronomy

The Stratospheric Observatory for Infrared Astronomy (SOFIA)³¹, the world's largest airborne observatory, is a partnership with Deutsches Zentrum für Luft- und Raumfahrt (DLR), the German space agency. The last 2 years have seen many changes for SOFIA. The HAWC+ instrument with polarization capabilities completed commissioning in 2017 and was made available for community use in Cycle 6 (2018–2019). The GREAT instrument was upgraded with new capabilities in 2018 to provide four new channels for observations in the far infrared, and these are available for community use in Cycle 7 (2019–2020). The HIRMES instrument passed CDR in 2017 and will begin commissioning its mid-infrared high spectral resolution capabilities in 2020. In early 2018, SOFIA retired two of its instruments (HIPO and FLITECAM). In November 2018, NASA selected proposals for instrument concept studies for major instrument upgrades. In 2017-2018, toward the end of Cycle 5, SOFIA had a longer-than-planned maintenance period that delayed the start of Cycle 6 observations to late Spring 2018 and the start of Cycle 7 observations to Spring 2019.

SOFIA's 5-year prime mission will be completed at the end of FY 2019. At the end of a prime mission, NASA assesses the science performance, management, and proposed future science program of its missions in order to decide on an extension of the program. This process is usually conducted through a Senior Review. However, the 2018 Consolidated Appropriations Act forbade NASA from placing SOFIA in the 2019 Senior Review. NASA will therefore conduct two alternative reviews of SOFIA to establish a productive and efficient extended mission:

- A review of SOFIA's operational paradigm to assure that SOFIA is optimally efficient and effective in planning and executing the science program; and
- A review of SOFIA's science progress and science prospects to assure that SOFIA is and will remain scientifically productive and relevant.

The results of these reviews will provide input into NASA's planning for SOFIA for FY 2020 and beyond. The reviews will not consider closeout or cancellation of SOFIA. The first review began in Fall 2018, and the second review will be conducted in early 2019.

7.2 Euclid

Euclid³² is an ESA mission to study the geometry and nature of the dark universe, slated for launch in 2022. NASA is providing 16 state-of-the-art infrared detector systems plus four spare units for the Near Infrared Spectrometer and Photometer (NISIP) instrument on Euclid. NASA also approved the Infrared Processing and Analysis Center (IPAC) to implement a Euclid NASA Science Center at IPAC (ENSCI)³³ to enhance the science return from the mission and to make Euclid data easily available to the entire U.S. science community. NASA selected three U.S. science teams to participate in the Euclid collaboration, and there are currently almost 100 U.S. scientists within the Euclid consortium.

Delivery of 20 flight-qualified detector units to ESA began in 2017. However, the original Sensor Chip Electronics (SCE) developed thermomechanical problems, so it required a redesign. The redesign is complete, and production of 20 new SCEs has started. They will be delivered to ESA

³¹ SOFIA mission homepage at <https://www.sofia.usra.edu/>.

³² NASA Euclid mission homepage at <https://euclid.jpl.nasa.gov/>.

³³ ENSCI homepage at <https://www.euclid.caltech.edu/>.

by the end of 2019. ENSCI continues to develop the U.S. science portal and provide portions of the Euclid ground station.

7.3 X-ray Imaging and Spectroscopy Mission

NASA initiated the X-ray Astronomy Recovery Mission (XARM) as a project, beginning formulation in October 2017, to recover the science lost when the Hitomi mission failed in March 2016. Following a confirmation review (KDP-C), XARM entered Phase C of its lifecycle in January 2018. The Japanese Aerospace and Exploration Agency (JAXA) approved XARM as a project in July 2018, following a project initiation review in which the mission was renamed X Ray Imaging and Spectroscopy Mission (XRISM)³⁴, a name also adopted by NASA.

XRISM will fly rebuilds of two of the original four Hitomi instruments, with a planned launch date of 2022. The soft X-ray microcalorimeter, called Resolve, is being rebuilt at GSFC where hardware activities are proceeding on schedule for an October 2019 delivery to JAXA. JAXA in partnership with ESA is rebuilding the wide field imaging instrument, called XTend, using mirrors contributed by NASA. The Canadian Space Agency (CSA) has joined XRISM as part of the U.S.-based team, contributing filter calibration activities at the Canada Light Source facility.

U.S.-based participating scientists were selected in February 2018 following an open call for proposals and peer review. These scientists are full members of the XRISM science team who, with their Japanese and European counterparts, are helping to establish the science priorities for the mission.

³⁴ NASA XRISM mission homepage at <https://heasarc.gsfc.nasa.gov/docs/xrism/>.

8. Recently Launched and Operating Missions

8.1 Neutron Star Interior Composition Explorer

The Neutron star Interior Composition Explorer (NICER)³⁵ was launched successfully on June 3, 2017, and installed robotically on the ISS. After 2 months of in-flight verification and calibration, NICER started observations of neutron stars and X-ray transients. NICER's 18-month prime operations ends in December 2018.

In June 2018, NICER successfully passed a Mission Progress Review, where it was established that the mission had successfully completed its Baseline Science and Technical Requirements. NASA granted NICER a “bridge” extension from January to September 2019 and invited the Project to participate in the 2019 Senior Review.

ANICER Guest Observers (GO) program has been established during the “bridge” phase. Additional GO cycles are planned if the NICER mission is extended following the 2019 Senior Review.

8.2 Transiting Exoplanet Survey Satellite

The Transiting Exoplanet Survey Satellite (TESS)³⁶ will spend 2 years discovering transiting exoplanets and other time-variable phenomena by an all-sky survey. TESS was launched on April 18, 2018, was injected subsequently into the planned high-Earth orbit, and began science operations in July 2018. TESS will monitor more than 200,000 stars for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets of all sizes. The TESS prime mission entails 2 years of on-orbit operations, with an additional year of ground-based astronomical follow-up observations.

In addition to the planned all-sky exoplanet survey, TESS will deliver full-frame images at a 30-minute cadence of the observational sectors that cover the sky. The TESS data will be made public in the Mikulski Archive for Space Telescopes (MAST) as soon as it is processed³⁷. A TESS GO program has been established to enable investigators to realize the science value of the full-frame images.

TESS will participate in the 2019 Senior Review.

³⁵ NICER mission homepage at <https://heasarc.gsfc.nasa.gov/docs/nicer/>.

³⁶ TESS mission homepage at <https://tess.gsfc.nasa.gov/>; TESS science team homepage at <https://tess.mit.edu/>.

³⁷ TESS data archive homepage at <https://archive.stsci.edu/tess/>.

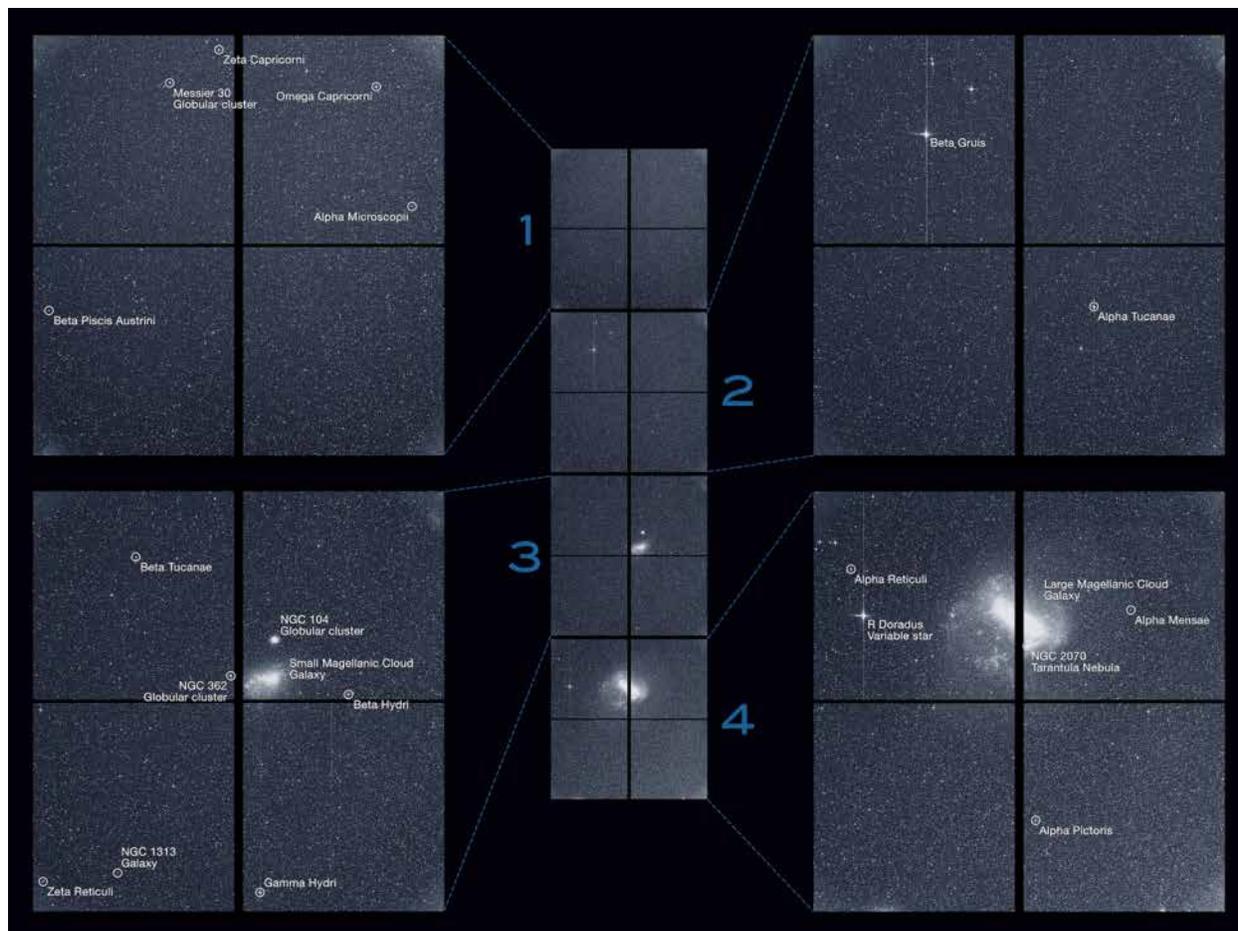


Figure 7. The Transiting Exoplanet Survey Satellite (TESS) captured this strip of stars and galaxies in the southern sky during one 30-minute period on Tuesday, Aug. 7, 2018. Created by combining the view from all four of its cameras, this is TESS’ “first light,” from the first observing sector that will be used for identifying planets around other stars. Notable features in this swath of the southern sky include the Large and Small Magellanic Clouds and a globular cluster called NGC 104, also known as 47 Tucanae. The brightest stars in the image, Beta Gruis and R Doradus, saturated an entire column of camera detector pixels on the satellite’s second and fourth cameras.

8.3 Cosmic Ray Energetics and Mass Experiment

The Cosmic Ray Energetics and Mass experiment³⁸ on the ISS (ISS-CREAM) was launched to the ISS on August 14, 2017, and installed on the Japanese Experiment Module-Exposed Facility (JEM-EF) shortly thereafter. ISS-CREAM will measure the origin, acceleration, and propagation of cosmic rays in the Galaxy. ISS-CREAM on-orbit science operation was planned for a 1-year prime mission with a possible extension of 2 more years. NASA conducted a continuation review of ISS-CREAM in September 2018.

³⁸ ISS-CREAM experiment homepage at <http://cosmicray.umd.edu/iss-cream/>.

8.4 2019 Senior Review

The next Senior Review of Operating Astrophysics Missions³⁹ will be in Spring 2019 with eight participating. The missions participating in the 2019 Senior Review are (in alphabetical order):

- Chandra X-ray Observatory,
- Fermi Gamma-ray Space Telescope,
- Gehrels Swift Gamma-ray Burst Explorer,
- Hubble Space Telescope,
- Neutron star Interior Composition Explorer (NICER),
- Nuclear Spectroscopic Telescope Array (NuSTAR),
- Transiting Exoplanet Survey Satellite (TESS), and
- X-ray Multi-Mirror Mission (XMM)-Newton (an ESA mission with U.S. participation).

The 2019 Senior Review will adopt a hybrid structure, in which three review panels will report to a Senior Review Subcommittee. The three review panels will examine Hubble, Chandra, and the other missions. The panels will evaluate the mission(s) based on their scientific merit, their relevance and responsiveness to NASA's strategic goals in astrophysics and science, and their expected technical capability and cost reasonableness over the next three years. The Senior Review Subcommittee has been established as a subcommittee of the Astrophysics Advisory Committee (Section 2). The Senior Review Subcommittee's principal role is to merge the findings from the three subpanels and to rank the missions; it will then submit its report to the Astrophysics Advisory Committee. After public deliberation of the Senior Review Report, the Astrophysics Advisory Committee will deliver a final report to NASA. The entire process is planned to be complete by May 2019.

8.5 Kepler Space Telescope

During its K2 mission extension, the Kepler Space Telescope used thrusters to make up for the lack of a third reaction wheel. On October 30, 2018, NASA announced that Kepler had run out of fuel, marking the end of mission operations⁴⁰. The legacy of the Kepler mission is clear: there are more planets than stars, and rocky planets in the habitable zone are common. The data from Kepler, both the prime mission and the K2 mission, are available to the science community in the Mikulski Archive for Space Telescopes (MAST)⁴¹.

³⁹ 2019 Senior Review homepage at <https://science.nasa.gov/astrophysics/2019-senior-review-operating-missions/>.

⁴⁰ Announcement of Kepler end-of-mission at <https://www.nasa.gov/press-release/nasa-retires-kepler-space-telescope-passes-planet-hunting-torch>.

⁴¹ Kepler archived data homepage at <https://archive.stsci.edu/kepler/>.

9. Planning for the 2020 Astrophysics Decadal Survey

9.1 Overview of Decadal Survey Planning

NASA-sponsored studies of Large and Medium (“Probes”) sized mission concepts are progressing toward submission of the final reports to NASA by June 2019 and January 2019, respectively. Relevant documents, as well as links to relevant websites, are posted on NASA’s 2020 Decadal Survey Planning homepage⁴².

In early 2018, NASA tasked the Committee on Astronomy and Astrophysics (CAA) to review NASA’s plans and preparations for the 2020 Decadal Survey and provide comments and suggestions for improvement. In their 2018 report⁴³, the CAA concurred with NASA’s process and listed seven findings for NASA and the Mission Concept Teams to consider.

NASA, NSF, and DOE (the Agencies) have established tasks (NASA) or grants (NSF, DOE) with the National Academies for the conduct of the 2020 Decadal Survey. The Agencies and the National Academies have finalized the Statement of Task (SOT) that the Decadal Survey Committee will follow⁴⁴. The 2020 Decadal Survey is being initiated in late 2018, will be presented to the community during a Town Hall at the Winter 2019 AAS meeting, and will take approximately 2 years to complete.

The SOT requires the National Academies to convene an ad hoc survey committee and supporting study panels to carry out a decadal survey in astronomy and astrophysics. The committee, with inputs from study panels covering the breadth of astronomy and astrophysics, will carry out five tasks (this text is an abridged version of the text in the SOT):

- Provide an overview of the current state of astronomy and astrophysics science.
- Identify the most compelling science challenges and frontiers in astronomy and astrophysics.
- Develop a comprehensive research strategy to advance the frontiers of astronomy and astrophysics that will include identifying, recommending, and ranking the highest priority research activities. The strategy should be balanced, by considering large, medium, and small activities for both ground and space.
- Utilize and recommend decision rules that can accommodate deviations in the projected budget or changes precipitated by new discoveries.
- Assess the state of the profession. Identify areas of concern and importance to the community. Where possible, provide specific, actionable and practical recommendations to the agencies and community to address these areas.

⁴² NASA’s 2020 Decadal Survey Planning homepage at <https://science.nasa.gov/astrophysics/2020-decadal-survey-planning/>.

⁴³ *Report Series: Committee on Astronomy and Astrophysics: Mission Concept Studies* (National Academies, 2019), <https://www.nap.edu/catalog/25212/>.

⁴⁴ National Academies 2020 Decadal Survey homepage, including the full Statement of Task, at <http://nas.edu/Astro2020>.

9.2 Large Strategic Mission Concept Studies

In 2016, NASA established Science and Technology Definition Teams (STDTs) to study four large strategic mission concepts. The STDTs of the four large strategic mission concept studies continue their work towards a delivery of the final report to NASA by June 2019. Two of the four Large Strategic Mission Concepts were renamed to reflect the breadth of their science: The Far Infrared Surveyor was renamed the Origins Space Telescope (OST)⁴⁵, and the X-ray Surveyor was renamed the Lynx X-ray Observatory⁴⁶. The Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR)⁴⁷ and the Habitable Exoplanet Imaging Mission (HabEx)⁴⁸ kept their original names.

As directed in the *Management Plan for Large Mission Concept Studies* (available at NASA's 2020 Decadal Survey Planning homepage), the four STDTs submitted an Interim Report in March 2018 to NASA. The Interim Reports were evaluated by an independent team of scientists and technologists with experience in the processes and procedures of mission concept studies and decadal surveys. The Interim Reports are publicly available through links at NASA's 2020 Decadal Survey Planning homepage.

In June 2018, NASA tasked the four STDTs to study alternative architectures to their primary design, in the spirit of offering options to the Decadal Survey Committee for different versions of the Large Mission Concepts. NASA desires an ambitious Decadal Survey process. The goal of these mission concept studies, including both architectures for each mission concept, is to provide the Decadal Survey with a range of possibilities to inform their recommendations of a compelling astrophysics program for the next decade. The STDTs will include both architectures in their final reports.

The four STDTs are working closely with engineering teams at the NASA Centers assigned to each study. The Center design labs have developed high-level mission concept design products and conducted independent cost estimates through their cost assessment offices. NASA assembled a Large Mission Concept Independent Assessment Team (LCIT) to conduct a technical, risk, and cost assessment of the four mission concept studies. The LCIT will use the four Large Mission Concept Draft Final Reports, the high-level design products, and the Center cost estimates. The LCIT includes experienced technical and cost reviewers with expertise in large space missions and in science, instrumentation, and technology. The *Terms of Reference* of the LCIT is available at NASA's 2020 Decadal Survey Planning homepage.

9.3 Astrophysics Probes Studies

The ten PI-led Probe mission concept studies are completing their work and each will submit a final report to NASA by December 2018.

NASA has requested GSFC's and JPL's costing offices to perform independent cost assessments of the Probe concept studies. In order to provide an independent, non-advocate assessment of the Probe studies, NASA is assembling an independent Probes Concept Assessment Team (PCAT). The PCAT will review the Probe studies, including the cost assessments provided by the costing offices. The PCAT includes experienced technical and cost reviewers with expertise in science, instrumentation, and technology. The *Terms of Reference* of the PCAT is available at NASA's 2020 Decadal Survey Planning homepage.

⁴⁵ Origins Space Telescope study homepage at <https://asd.gsfc.nasa.gov/firs/>.

⁴⁶ Lynx X-ray Observatory study homepage at <https://wwwastro.msfc.nasa.gov/lynx/>.

⁴⁷ Large UV/Optical/IR Surveyor study homepage at <https://asd.gsfc.nasa.gov/luvoir/>.

⁴⁸ Habitable Exoplanet Imaging Mission study homepage at <https://www.jpl.nasa.gov/habex/>.

9.4 Other NASA Preparations

The NASA Astrophysics Division is sponsoring, planning, or contemplating several additional studies as input to the 2020 Decadal Survey. These are independent of studies being initiated and conducted by NASA scientists at NASA Centers without Astrophysics Division sponsorship.

These additional studies include:

- Scientific Balloon Roadmap⁴⁹. In preparation for the upcoming 2020 Decadal Survey, the Astrophysics Division has called on the community of scientific ballooning users across NASA's Science Mission Directorate (Earth, Planetary, Heliophysics, and Astrophysics) to submit white papers detailing the scientific potential that could be enabled with present and future Balloon Program capabilities. The scientific ballooning users community is also providing direct comments and input through Scientific Ballooning Townhall meetings at major scientific conferences. This Roadmap document will highlight the scientific goals that can be enabled by the Balloon Program and what capabilities will be needed to achieve them, and it will serve as a strategic plan for the Balloon Program Office.
- Evolution of NASA Data Centers. This set of studies draw on efforts including an STScI study on big data⁵⁰, NASA Advisory Council Big Data Task Force reports on adapting archives to technology⁵¹, and an IPAC-led cross-agency study to scope out the costs and benefits of processing data from WFIRST/LSST/Euclid jointly to maximize the benefits for cosmological studies. In addition, SMD has convened a Strategic Data Management Working Group (SDMWG) to develop a strategic plan for scientific data and computing to guide the evolution of SMD data and computing systems over the next 5 years; the NASA astrophysics data centers are contributing input that will be incorporated into the development of the new plan.
- In-Space Servicing/In-Space Assembly Study⁵². This study aims to answer the question: "When is it advantageous to assemble space telescopes in space rather than to build them on the Earth and deploy them autonomously from individual launch vehicles?" The study will provide input to the 2020 Decadal Survey, to inform discussions about future large space observatories.

⁴⁹ Balloon Roadmap updates posted at https://sites.wff.nasa.gov/code820/roadmap_pag.html.

⁵⁰ https://archive.stsci.edu/reports/BigDataSDTReport_Final.pdf

⁵¹ <https://science.nasa.gov/science-committee/subcommittees/big-data-task-force>

⁵² In-Space Servicing/In-Space Assembly study homepage at https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/.

10. Summary

This Update summarizes, as of December 2018, events and developments since December 2016 that affect NASA's plans for achieving its strategic objectives in astrophysics and its progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*, including preparation for the 2020 Astrophysics Decadal Survey.

As recognized by the National Academies' Midterm Assessment, NASA has made substantial progress in implementing the recommendations of the 2010 Decadal Survey and providing an overall balanced program. The Webb observatory's combined telescope and instruments successfully completed testing, but the spacecraft element encountered issues related to integration and testing that delayed the expected launch date to March 2021. WFIRST made changes following the Midterm Assessment's recommended independent review and is now in Phase B; however, WFIRST has been proposed for termination in the President's FY 2019 budget request to accommodate other priorities. The notional planning budget for NASA Astrophysics provided in the FY 2019 budget request accommodates an increase in the cadence of Astrophysics Explorers Program AOs that meets the Decadal Survey's recommendation for four AOs per decade, with each AO leading to the selection of a mission and a mission of opportunity. The notional planning budget also accommodates continued growth in NASA's astrophysics R&A programs.

ESA and NASA are finalizing a NASA contribution to the ESA-led Athena X-ray Observatory. NASA continues to support technology investments towards its hardware contribution to the ESA-led LISA gravitational wave observatory; as recommended by the Midterm Assessment, NASA has increased the scope of its participation in LISA.

NASA is carrying out mission concept studies and technology development, including the "New Worlds Technology" development recommended in the 2010 Decadal Survey, that will inform the 2020 Astrophysics Decadal Survey.

During the current decade, exciting discoveries and substantial progress has been made in advancing the science priorities of *New Worlds, New Horizons*. Disciplines including exoplanet research, gravitational wave astrophysics, cosmology, multimessenger astronomy, and many others have been substantially changed through the research opportunities and space missions that NASA has made available. In that same spirit, NASA is prepared to implement the recommendations of the upcoming Decadal Survey.

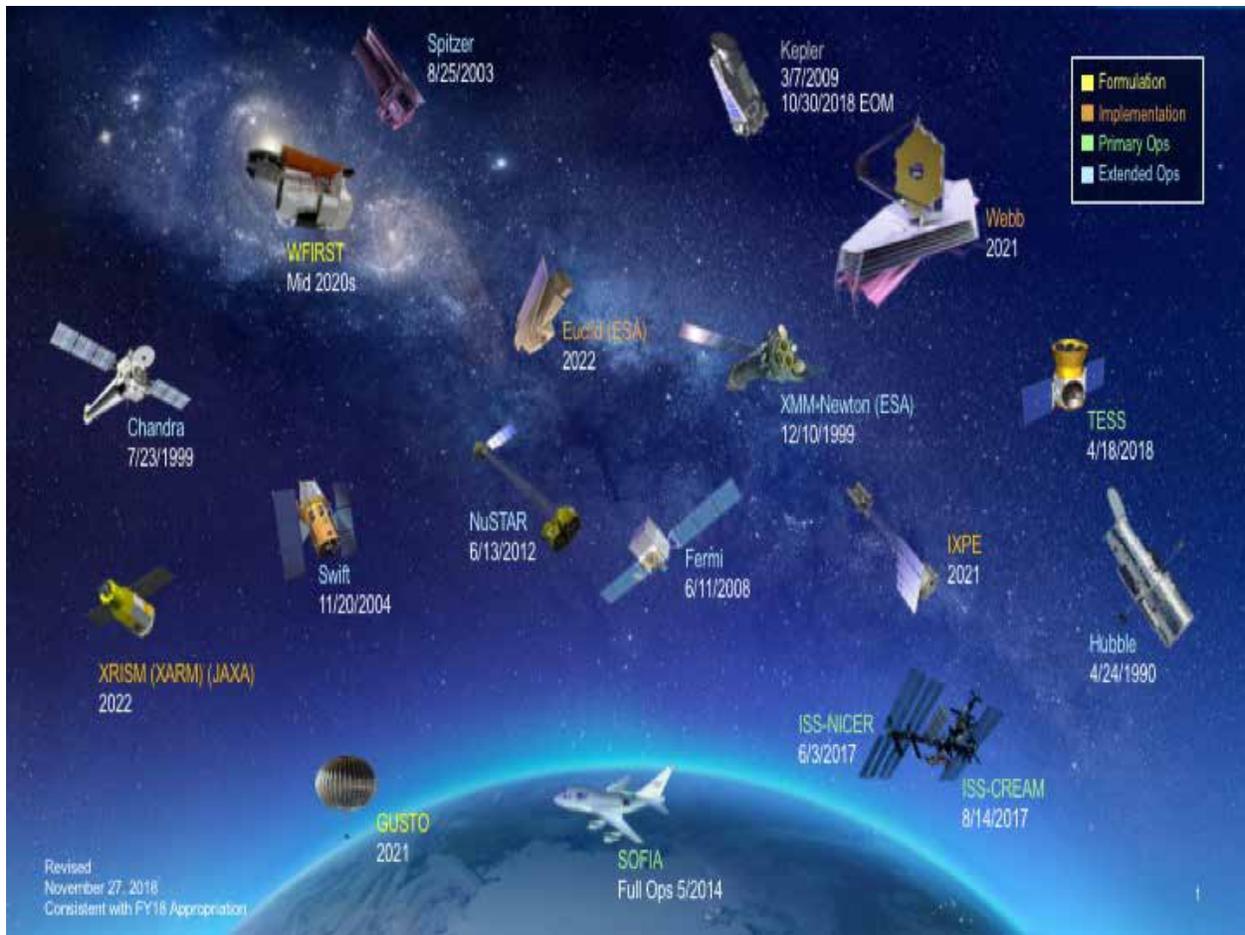


Figure 8. Astrophysics missions as of November 2018.

Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
AO	Announcement of Opportunity
APAC	Astrophysics Advisory Committee
APRA	Astrophysics Research and Analysis
ASIC	Application Specific Integrated Circuit
CAA	Committee on Astronomy and Astrophysics
CDR	Critical Design Review
CGI	Coronagraph Instrument (on WFIRST)
CMB	Cosmic Microwave Background
CREAM	Cosmic Ray Energetics and Mass experiment
CSA	Canadian Space Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DOE	Department of Energy
EELV	Evolved Expendable Launch Vehicle
ENSCI	Euclid NASA Science Center at IPAC
EPDS	Extreme Precision Doppler Spectrometer (on WIYN Telescope)
ESA	European Space Agency
ESPA	EELV Secondary Payload Adapter
FLITECAM	First Light Infrared Test Experiment Camera (SOFIA)
FSWG	Formulation Science Working Group
FY	Fiscal Year
GSFC	Goddard Space Flight Center
GO	Guest Observer
GREAT	German Receiver for Astronomy at Terahertz Frequencies (SOFIA)
GUSTO	Galactic/Extragalactic ULDB Spectroscopic Terahertz Observatory
HabEx	Habitable Exoplanet Imaging Mission
HAWC+	High-resolution Airborne Wideband Camera-plus (SOFIA)
HEOMD	Human Exploration and Operations Mission Directorate
HIPO	High-speed Imaging Photometer for Occultations (SOFIA)
HIRMES	High Resolution Mid-Infrared Spectrometer (SOFIA)
IPAC	Infrared Processing and Analysis Center
ISS	International Space Station
ISS-CREAM	CREAM on ISS
IXPE	Imaging X-ray Polarimetry Explorer
JAXA	Japan Aerospace Exploration Agency
JEM-EF	Japanese Experiment Module-Exposed Facility
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
KDP	Key Decision Point
LBTI	Large Binocular Telescope Interferometer
LCIT	Large Mission Concept Independent Assessment Team
LDB	Long-Duration Balloon
LISA	Laser Interferometer Space Antenna
LPS	LISA Preparatory Science

LSST	Large Synoptic Survey Telescope
LUVOIR	Large Ultraviolet/Optical/Infrared Surveyor
MAST	Mikulski Archive for Space Telescopes
MCR	Mission Concept Review
MDR	Mission Design Review
MIDEX	Medium-class Explorer
MO	Mission of Opportunity
MSFC	Marshall Space Flight Center
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NEID	NN-EXPLORE Exoplanet Investigations with Doppler spectroscopy
NExSS	Nexus for Exoplanet System Science
NICER	Neutron star Interior Composition Explorer
NISP	Near Infrared Spectrometer and Photometer (Euclid)
NLST	NASA LISA Study Team
NN-EXPLORER	NASA-NSF Exoplanet Observational Research partnership
NOAO	National Optical Astronomy Observatories
NSF	National Science Foundation
NuSTAR	Nuclear Spectroscopic Telescope Array
OST	Origin Space Telescope
PCAT	Probes Concept Assessment Team
PCOS	Physics of the Cosmos
PDR	Preliminary Design Review
PI	Principal Investigator
PIPER	Primordial Inflation Polarization Explorer
R&A	Research & Analysis
S5	Starshade to TRL-5 technology development activity
SAT	Strategic Astrophysics Technology
SCE	Sensor Chip Electronics (Euclid)
SDMWG	Strategic Data Management Working Group
SMD	Science Mission Directorate
SMEX	Small-class Explorer
SOC	Science Operations Center
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPB	Super-Pressure Balloon
SRR	System Requirements Review
SSB	Space Studies Board
SST	Science Study Team
STDT	Science and Technology Definition Team
STMD	Space Technology Mission Directorate
STScI	Space Telescope Science Institute
SWG	Science Working Group
TCAN	Theoretical and Computational Astrophysics Network
TESS	Transiting Exoplanet Survey Satellite
TRL	Technology Readiness Level
ULDB	Ultra Long Duration Balloon
WFI	Wide Field Instrument
WFIRST	Wide Field Infrared Survey Telescope
WIETR	WFIRST Independent External Technical/Management/Cost Review

WIYN	Wisconsin-Indiana-Yale-NOAO telescope
XARM	X-ray Astronomy Recovery Mission
X-IFU	X-ray Integral Field Unit (Athena)
XMM-Newton	X-ray Multi-Mirror Mission-Newton
XRISM	X-ray Imaging and Spectroscopy Mission
XRP	Exoplanet Research Program