National Aeronautics and Space Administration

Astrophysics Implementation Plan: 2016 Update

This Update provides a summary since the publication of the *Astrophysics Implementation Plan: 2014 Update* in December 2014, of events and developments that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

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

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Contents

1. Introduction and Purpose

This Update provides a summary, since the publication of the *Astrophysics Implementation Plan: 2014 Update*[1] in December 2014, of events and developments that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*[2]

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

[1] *Astrophysics Implementation Plan: 2014 Update* (NASA, December 2014), http://science.nasa.gov/astrophysics/documents/.
[2] *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010), https://www.nap.edu/download/12951.
[3] *Astrophysics Implementation Plan* (NASA, December 2012), http://science.nasa.gov/astrophysics/documents.

2. Summary of Changes since December 2014

NASA continues to make substantial progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*, hereafter NWNH. As recognized by the 2016 Midterm Assessment Report (see Section 3), the NASA astrophysics portfolio is well balanced and contains a mix of large-, medium-, and small-scale activities. Some of the important accomplishments since 2014 are listed here and described in more detail in subsequent sections.

- The James Webb Space Telescope (JWST), the highest priority large space mission of the 2001 Astrophysics Decadal Survey, *Astronomy and Astrophysics in the New Millennium*[4], remains on schedule and within budget for a launch in October 2018 (see Section 8.1).
- The Wide-Field Infrared Survey Telescope (WFIRST) entered the formulation phase in February 2016. In addition, NASA established the WFIRST Formulation Science Working Group with the goal of defining the mission science investigations and the top-level mission requirements (see Section 4).
- Three Small Explorer (SMEX) proposals and two Explorer Mission of Opportunity proposals were selected in 2015 for Phase A mission concept studies from among proposals submitted to NASA in response to the 2014 Astrophysics Small Explorers Announcement of Opportunity (AO); the final down-selection is planned for January 2017 for the SMEX mission and for Spring 2017 for the Explorer Mission of Opportunity (see Section 5).
- The NASA-provided Disturbance Reduction System was launched on the European Space Agency (ESA)-led LISA Pathfinder mission on December 3, 2015, and successfully met its science success requirements (see Section 8.5). NASA moved forward with plans to participate in a future ESA-led gravitational wave observatory by establishing the U.S. L3 Study Team, establishing the NASA L3 Study Office, and continuing to develop technology applicable to a space-based gravitational wave observatory (see Section 6.1).
- NASA plans to partner in ESA's Athena X-ray Observatory by contributing elements of both instruments and possibly other items (see Section 6.2).
- The Stratospheric Observatory for Infrared Astronomy (SOFIA) instrument suite is being upgraded with the commissioning of new instruments that expand the airborne infrared observatory's capabilities (see Section 8.2).
- The Japan Aerospace Exploration Agency (JAXA)-led ASTRO-H mission was launched on February 17, 2016, and renamed Hitomi. During commissioning, but after demonstrating the full science capabilities of the NASA-provided Soft X-ray Spectrometer, Hitomi failed due to an onboard anomaly. JAXA is considering an X-ray Astronomy Recovery Mission with NASA participation (see Section 8.3).

[4] *Astronomy and Astrophysics in the New Millennium* (NRC, 2001), https://www.nap.edu/download/9839.

- The 2016 Senior Review recommended that NASA continue all operating missions (see Section 8.4).
- Missions under development continued their progress toward launch. The Transiting Exoplanet Survey Satellite (TESS) held a successful Critical Design Review in August 2015 (see Section 8.6.1). The Neutron star Interior and Composition Explorer on the International Space Station (NICER) held a successful Operational Readiness Review in October 2016 (see Section 8.6.2). The launches of NICER and the Cosmic Ray Energy and Mass experiment on the International Space Station (ISS-CREAM) are scheduled for 2017 (see Sections 8.6.2 and 8.6.3).
- NASA has begun mission concept studies in preparation for the 2020 Decadal Survey. NASA has initiated four mission concept studies for large-scale strategic (see Section 9.1) and is initiating mission concept studies for medium-scale missions (Astrophysics Probes) (see Section 9.2).

Decadal Survey Recommendation	NASA Actions
Large-scale 1. WFIRST	In Phase A, launch in mid-2020s (see Section 4)
Large-Scale 2. Augmentation to Explorer Program	Executing 4 Announcements of Opportunity (AOs) per decade (see Section 5)
Large-Scale 3. LISA	Partnering on ESA's space-based gravitational wave observatory (see Section 6.1)
Large-Scale 4. IXO	Partnering on ESA's Athena X-ray observatory (see Section 6.2)
Medium-Scale 1. New Worlds Technology Development Program	WFIRST coronagraph; starshade and coronagraph technology development; Doppler spectrograph on WIYN telescope; exozodiacal dust survey with LBTI (see Section 7.1)
Medium-Scale 2. Inflation Probe Technology Development Program	Multiple balloon-borne investigations plus SAT investments (see Section 7.2)
Small-Scale. Research Program Augmentations	R&A as of FY2016 up 20% from FY2010; increase not targeted except TCAN (see Section 7.3)
Small-Scale. Intermediate Technology Development Augmentation	Initiated Strategic Astrophysics Technology program; focused on identified strategic missions
Small-Scale. SPICA (U.S. contribution)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity

Table 1. Recommended space activities of the 2010 Decadal Survey supported by the FY 2016 NASA Appropriation, the FY 2017 President's Budget Request, and its notional out year planning budget.

3. The Midterm Assessment

The NASA Authorization Act of 2005 requires NASA to task the National Academies with a study reviewing NASA's progress in implementing each decadal survey midway through the decade. In 2015, the National Academies appointed the Committee on the Review of Progress Toward the Decadal Survey Vision in New Worlds, New Horizons in Astronomy and Astrophysics to conduct this midterm assessment. On August 15, 2016, the committee released its report, *New Worlds, New Horizons, A Midterm Assessment*[5] (hereafter the Midterm Assessment).

The Midterm Assessment included several findings and recommendations for NASA. The Midterm Assessment finds that, "Despite a challenging budget environment, NASA [Astrophysics] has maintained a balanced portfolio through the first half of the decade and, with the assumption of successful completion of an ambitious Explorer schedule, will do so during the second half of the decade as well."[6]

Table 2 summarizes the recommendations in the Midterm Assessment and summarizes NASA's planned actions. Additional updates based on the Midterm Assessment findings for specific medium- and small-size activities are reported in Section 7 below (Boxes 7.1, 7.2, and 7.3).

NASA Activity	Midterm Assessment Recommendations	NASA Response
WFIRST	Recommendation 4.1: Prior to Key Decision Point B, NASA should commission an independent technical management, and cost assessment of the Wide-Field Survey Telescope, including a quantitative assessment of the incremental cost of the coronagraph. If the mission cost estimate exceeds the point at which executing the mission would compromise the scientific priorities and the balanced astrophysics program recommended by [NWNH], then NASA should descope the mission to restore the scientific priorities and program balance by reducing the mission cost.	NASA agrees with the Committee. NASA plans to conduct an independent technical, management, and cost assessment of WFIRST prior to KDP-B. NASA will continue to manage WFIRST and the overall astrophysics portfolio to maintain program balance (see Section 4).
Euclid	Recommendation 4.2: In the remainder of the decade, NASA should treat support of Euclid participation beyond the existing commitments to [ESA] as lower priority than support of the Explorers Program, gravitational wave technology development, and X-ray technology development.	NASA will treat growth in Euclid elements beyond hardware (e.g., the U.S. node in the Euclid science ground system and the U.S. Euclid science center, support for U.S. science team) as lower priority. At the appropriate time, NASA will discuss with the Committee on Astronomy and Astrophysics whether this means that no funded Euclid General Observer (GO) program can be initiated for the U.S. community (see Section 8.6.4).

* *Table 2 continues on next page.*

Table 2. Recommendations of the 2016 Midterm Assessment and NASA's response.

[5] *New Worlds, New Horizons, A Midterm Assessment,* (NRC, 2016), https://www.nap.edu/download/23560.
[6] Midterm Assessment, ibid, Finding 4-14.

** Table 2 continued.*

NASA Activity	Midterm Assessment Recommentations	NASA Response
Astrophysics Explorers	Recommendation 4.3: NASA's Astrophysics Division should execute its current plan, as presented to the committee, of at least four Explorers [Announcements of Opportunity] during the 2012-2021 decade, each with a [Mission of Opportunity] call, and each followed by mission selection.	NASA agrees with the Committee. NASA issued an Astrophysics Small Explorer (SMEX) AO in 2014 and an Astrophysics Medium-class Explorer (MIDEX) AO in 2016. NASA is currently planning to issue an Astrophysics SMEX AO in 2019 and an Astrophysics MIDEX AO in 2021. NASA plans for each of those Astrophysics Explorers mission AOs to be accompanied by a Mission of Opportunity AO (see Section 5).
LISA (ESA L3)	Recommendation 4.4: NASA should restore support this decade for gravitational wave research that enables the U.S. community to be a strong technical and scientific partner in the [ESA]-led L3 mission, consistent with the [LISA]'s high priority in the 2010 report [NWNH]. One goal of U.S. participation should be the restoration of the full scientific capability of the mission as envisioned by NWNH.	NASA has begun discussions within the U.S. Government on committing to a larger role for the U.S. in the L3 mission. ESA is open to a larger role for the U.S., subject to ESA's established constraints on international partnerships (international contributions are limited to 20%, and all international contributions require a European backup). NASA has begun discussions within the Government on committing to a larger role for the U.S. in the L3 mission. Any changes in out-year planning are subject to the limitations of the out-year planning budget, i.e., the notional out-year planning budget is flat. NASA is reviewing options for L3-relevant technology investments through the Strategic Astrophysics Technology (SAT) and other programs. NASA is also reviewing options for reduced funding of exoplanet technology development beyond the WFIRST coronagraph, if this is necessary to enable appropriate investments in gravitational wave research and technology (see Section 6.1).
Athena (ESA L2)	Recommendation 4.5: NASA should proceed with its current plan to participate in Athena, with primary contributions directed toward enhancing the scientific capabilities of the mission.	NASA agrees with the Committee. NASA intends its contributions to the ESA Athena mission to enhance the science return of the mission, when compared to an Athena mission without NASA participation. NASA plans to contribute to both the X-ray Integral Field Unit instrument and the Wide Field Imager instrument, as well as contribute to the observatory and mission (see Section 6.2).

Table 2. Recommendations of the 2016 Midterm Assessment and NASA's response.

4. Wide-Field Infrared Survey Telescope

The Wide-Field Infrared Survey Telescope (WFIRST)[7] is a mission designed to address essential questions in the areas of dark energy, exoplanets, and infrared astrophysics. WFIRST is designed to perform wide field imaging and surveys of the near infrared sky. The mission makes use of an existing 2.4 m telescope, which is the same size as the Hubble telescope. WFIRST is the top-ranked large space mission in the 2010 Decadal Survey. The Wide Field Instrument will provide a field of view of the sky that is 100 times larger than images provided by Hubble. The technology demonstration Coronagraph Instrument will enable astronomers to detect and measure properties of planets in other solar systems.

Following a successful Mission Concept Review (MCR) in December 2015, WFIRST held a successful Key Decision Point A (KPD-A) review on February 17, 2016, formally progressing from a study to an official NASA project. In December 2015 NASA established the WFIRST Science Investigation Teams (SITs). The SIT principal investigators and adjutant scientists constitute the WFIRST Formulation Science Working Group (FSWG). The FSWG is responsible for defining in detail the mission science investigations (the development of scientific performance requirements, the design of preliminary observing programs, the development of science data analysis techniques, and the development of simulations and data challenges to validate the aforementioned), and it is responsible for working with the WFIRST Project to define the top-level mission requirements.

Since KDP-A, the project has made excellent technical progress. The FSWG has completed a near-final version of the Science Requirements Document, which serves as the basis for the Mission Requirements Document. In addition, the project has sustained very good performance against the technology milestones for the near-infrared detectors and the coronagraph flight demonstration. As validated by an external technology assessment committee, the coronagraph technologies (system/subsystem/component validation in relevant environment) are expected to achieve TRL-5 by early 2017. The milestone of TRL-6 (prototyping demonstration in a relevant end-to-end environment) on the near-infrared detectors for the wide field instrument is also anticipated to be achieved in early 2017, over two years in advance of when this level of maturity is required by NASA standards. The project is on track for a successful System Requirements Review (SRR) in June 2017. The SRR will be the first WFIRST review conducted by the project's Standing Review Board (SRB). Figure 1 shows a timeline for WFIRST with preliminary planning dates for major lifecycle events.

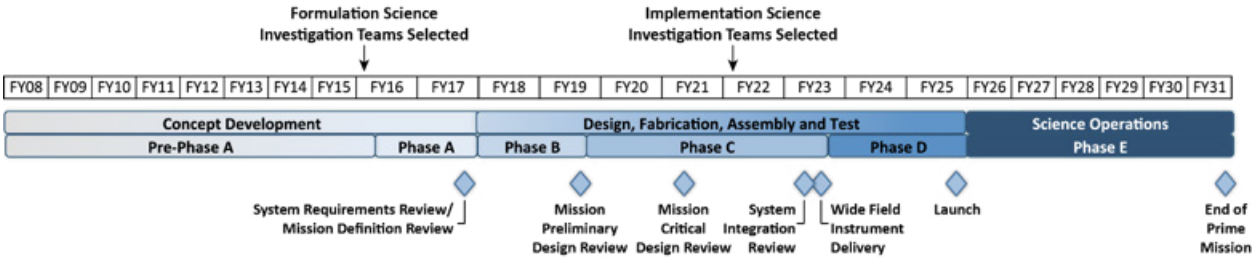

Figure 1. Preliminary timeline for the WFIRST mission highlighting major events in the project lifecycle. All dates are notional, but illustrate the sequence of events referred to in the text.

[7] WFIRST homepage at http://wfirst.gsfc.nasa.gov/.

5. Astrophysics Explorers

The two Explorers missions that were down-selected 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 – have continued their implementation toward launch (see Sections 8.6.1 and 8.6.2).

The AOs[8] that were released in September 2014 for SMEX and Mission of Opportunity (MO) proposals resulted in the 2015 selection of three SMEXs and two MOs 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 down-selection of one SMEX mission is anticipated in January 2017, and the down-selection of one MO is anticipated in Spring 2017.

AOs[9] for MIDEX and MO proposals were released in September 2016, with selections for nine-month Phase A Concept Studies anticipated in the summer of 2017, and down-selection for flight expected by early 2019. Subsequent AOs, each for a mission and a MO, are anticipated every 2-3 years.

[8] 2014 Astrophysics Explorers 2014 AO acquisition page at https://explorers.larc.nasa.gov/APSMEX/.
[9] 2014 Astrophysics Explorers 2014 AO acquisition page at https://explorers.larc.nasa.gov/APMIDEX2016/.

6. Decadal Survey Large-Scale Prioritized Activities

6.1 Space-based Gravitational Wave Observatory

NASA continued its discussions with ESA concerning a possible hardware contribution as a minority partner to ESA's Large-3 (L3) mission, a gravitational wave observatory. To this end, in January 2016 NASA established the U.S. L3 Study Team (L3ST)[10]. The L3ST is chartered to analyze the options for NASA participation in the L3 mission, work with the European L3 consortium on the mission proposal to ESA (call for mission proposals[11] released in October 2016), and prepare a report to the 2020 Decadal Survey on NASA's participation as a partner in the L3 mission. The L3ST recently released its interim report[12] with an analysis of the possible U.S. contributions to L3, as well as a Technology Roadmap detailing a plan for NASA to develop these technologies to a sufficient level of maturation for ESA mission adoption.

In August 2016, the Midterm Assessment (see Section 3) recommended that NASA seek an increased participation level on the L3 mission, with the goal of enabling the U.S. to be "a strong technical and scientific partner in the ESA-led L3 [gravitational wave] mission."[13] As a result, NASA is studying an increase in its level of contribution to L3, within the ESA-imposed contribution cap of 20% of the total mission cost. NASA is also continuing to support development of technology relevant to a space-based laser interferometer, and has established an L3 Study Office at Goddard Space Flight Center (GSFC) to coordinate the L3 activities.

6.2 Athena X-ray Observatory

In July 2014 ESA formed an Athena Science Study Team (SST) whose main task is providing guidance on all scientific aspects as a mission architecture is developed during the Assessment Phase. NASA appointed a U.S. member of the Athena SST in late July 2014 after soliciting nominations from the community through a "Dear Colleague Letter." The Athena SST's remit includes acting as a focus for the involvement of the broad scientific community. The Athena SST has established an Athena Science Working Group (SWG) structure populated by members of the European and U.S. community. Nominations for U.S. working group members were solicited by NASA through a "Dear Colleague Letter" in November 2014; as of December 2016, there are nearly 100 U.S. members, 25 of whom were competitively selected to be funded by NASA for travel to Athena SWG meetings. U.S. membership in the Athena SWGs continues to grow. NASA plans to fund U.S. members of the Athena science team, U.S. science data center, and U.S. general observers during mission operation.

In December 2014, NASA issued a Request for Information (RFI) for hardware contributions to the two Athena instruments, the X-ray Integral Field Unit (X-IFU) and the Wide Field Imager (WFI), and indicated that out-year budget planning supports a hardware contribution at the $100-$150M level. Subsequently, two U.S. teams were selected to study possible contributions. A team led by GSFC will provide the microcalorimeter sensor unit for the X-IFU Demonstration Module

[10] L3ST membership and charter at https://pcos.gsfc.nasa.gov/studies/L3.
[11] ESA L3 mission call at http://www.cosmos.esa.int/web/2016-l3-mission-call.
[12] L3ST interim report at https://pcos.gsfc.nasa.gov/studies/L3/.
[13] Midterm Assessment, *ibid*, Recommendation 4-4.

and is studying provision of the flight microcalorimeter sensor unit. The X-IFU Demonstration Module is to be completed and tested in 2019. A team led by Pennsylvania State University is studying the provision of a WFI Science Products Module and Application Specific Integrated Circuit (ASIC) design. NASA provision of the WFI primary structure will also be studied in the 2017-2018 timeframe. NASA and ESA continue discussions on possible additional NASA contributions to Athena. ESA adoption of the Athena mission is planned for 2020.

NASA has established a NASA Athena Study Office at GSFC to coordinate the U.S. Athena activities.

7. Decadal Survey Medium- and Small-Scale Prioritized Activities

7.1 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 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 WFIRST coronagraph directed technology development program was established in 2013 to mature the technology required for the WFIRST coronagraph instrument. In 2016, NASA established a starshade technology development activity with the goal of advancing starshade technology for consideration by the 2020 Decadal Survey.

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. In 2014, NASA and NSF partnered to focus the National Optical Astronomy Observatory (NOAO) share of the 3.5-m WIYN telescope on Kitt Peak on the conduct of ground-based observations that advance exoplanet science. NASA is developing an Extreme Precision Doppler Spectrometer (EPDS) to be installed as a facility-class instrument on the WIYN telescope; the EPDS instrument is scheduled for commissioning in 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 is continuing its investment in the Large Binocular Telescope Interferometer (LBTI) and the associated survey of exozodiacal dust levels around a set of nearby stars.

In January 2013, NASA established two Science and Technology Definition Teams (STDTs) to study the feasibility of possible medium-size missions (total mission cost less than $1B) for direct imaging of exoplanets. The two STDTs were focused on studies of missions including coronagraph and starshade systems, respectively. The STDTs submitted their final reports[14] to NASA in March 2015. The initial concept studies were subsequently extended for the purposes of comparing the performance of the baseline design reference missions to that of an analogous mission based on WFIRST; the reports[14] of the extended studies were delivered to NASA in April 2016.

Precursor science activities necessary for a future exoplanet imaging mission are supported through the Exoplanet Research Program (XRP).

[14] Exoplanet Probe Science and Technology Definition Teams home page at https://exoplanets.nasa.gov/exep/studies/probe-scale-stdt/.

NASA Activity	Midterm Assessment Finding	NASA Response
New Worlds Technology Development	Finding 4-11: The current planned decadal investment in NWNH-recommended technology development and precursor science exceeds the level envisioned in NWNH.	NASA is reviewing options for reduced funding of exoplanet technology development beyond the WFIRST coronagraph, if this is necessary to enable appropriate investments in gravitational wave research and technology.

Box 7.1. Midterm Assessment for New Worlds Technology Development.

7.2 Inflation Probe Technology Development Program

NASA is supporting three Cosmic Microwave Background (CMB) polarization balloon projects.[15] Two flights have occurred in December 2012/January 2013 and December 2014/January 2015. Multiple flights are planned for the next three years. If successful, initial results are expected to be published by the end of the decade from multiple teams.

NASA is also supporting CMB polarization technology development, particularly those that exploit superconducting detectors, through the APRA and SAT programs. The more mature technologies are supported via the SAT program for the Physics of the Cosmos Program, which publishes a Program Annual Technology Report[16] summarizing the status of supported projects. APRA has supported and continues to advance 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 Activity	Midterm Assessment Finding	NASA Response
Inflation Probe Technology Development	Finding 4-12: The Inflation Probe Technology Development program is well aligned with the recommendations of NWNH, with NASA, NSF, and DOE supporting technology development and precursor science. Third-generation ground-based efforts and a suborbital program are taking place, targeting CMB B-mode polarization. The proposed CMB-S4 program would push the limits of what can be achieved from the ground and advance understanding of the technology and science requirements for a possible future space mission.	NASA agrees with the Committee. NASA will continue investing in inflation probe technology for a future CMB polarization space mission. NASA will monitor the CMB-S4 program being conducted by the National Science Foundation and the Department of Energy, in order to ensure synergy between ground and space based cosmic microwave background research.

Box 7.2. Midterm Assessment for Inflation Probe Technology Development.

[15] CMB polarization balloon projects: SPIDER (https://spider.princeton.edu); PIPER (http://asd.gsfc.nasa.gov/piper/); EBEX (http://groups.physics.umn.edu/cosmology/ebex/).

[16] Physics of the Cosmos Program Annual Technology Report at https://pcos.gsfc.nasa.gov/docs/, cf. pages 166-178.

7.3 Research and Analysis

After a 12% increase for Research and Analysis (R&A) in FY 2012, funding for the research award programs was maintained at this higher level through FY 2014, with a further 8% increase in FY 2016. Funding for R&A is up 20% in FY 2016 since the 2010 Decadal Survey. The FY 2017 President's Budget Request[17] requests another 4.5% increase beyond the level of FY2016, which would bring R&A funding to a 25% increase since the 2010 Decadal Survey. The average proposal acceptance rate for the four largest ROSES competitions administered by the Astrophysics Division (Astrophysics Data Analysis Program (ADAP), Astrophysics Research and Analysis (APRA), Astrophysics Theory Program (ATP), and Exoplanet Research Program (XRP)) in 2015-2016 is 22%.

Six networks were selected in FY 2013 for funding under the Theory and Computational Astrophysics Networks (TCAN) program, run jointly with the NSF Astronomical Sciences Division. A second solicitation for TCAN is planned for FY 2018.

NASA Activity	Midterm Assessment Finding	NASA Response
Small-scale Activities	Finding 4-13: NASA's implementation of NWNH's recommended small-scale activities has been mixed. Some recommended augmentations have not occurred and there have been cuts in some programs recommended for augmentation. Other programs, in particular the suborbital and exoplanet areas, have seen increases in excess of what was recommended by NWNH.	Since the Decadal Survey, NASA has increased funding for its core Research and Analysis (R&A) programs by 20% as of FY2016, and continued growth is planned through the end of the decade. This growth has not been targeted to specific Decadal Survey recommendations, with the exception of the creation of the Theory and Computational Astrophysics Networks (TCAN) program, a specific Decadal Survey recommendation. The allotment of the increased funding among those research elements targeted for growth by the Decadal Survey has been driven by the quality of proposed investigations as determined by peer review and by programmatic considerations.

Box 7.3. Midterm Assessment for Small-scale Activities.

[17] NASA FY 2017 Budget Request at http://www.nasa.gov/news/budget/.

8. Other Activities within Astrophysics

8.1 James Webb Space Telescope

The James Webb Space Telescope (JWST)[18] continues to make good progress toward meeting its planned launch date of October 2018. The Webb telescope recently completed all of its hardware fabrication; what remains in 2017 and 2018 is assembly and test. During 2016, the Integrated Science Instrument Module has been integrated with the Optical Telescope Element, forming the Webb Telescope science payload. The science payload is beginning its ambient testing prior to thermal vacuum testing at the Johnson Space Center (JSC) in 2017. The project also started the final JSC thermal vacuum test of the pathfinder telescope backplane and ground support equipment in preparation for the flight hardware next year.

During 2016, the Webb Telescope project took delivery of all the flight sunshield membranes and began integration of spacecraft subsystems. The project is well poised for the 2017 major activities, cryogenic testing of the science payload, and integration of the sunshield and spacecraft.

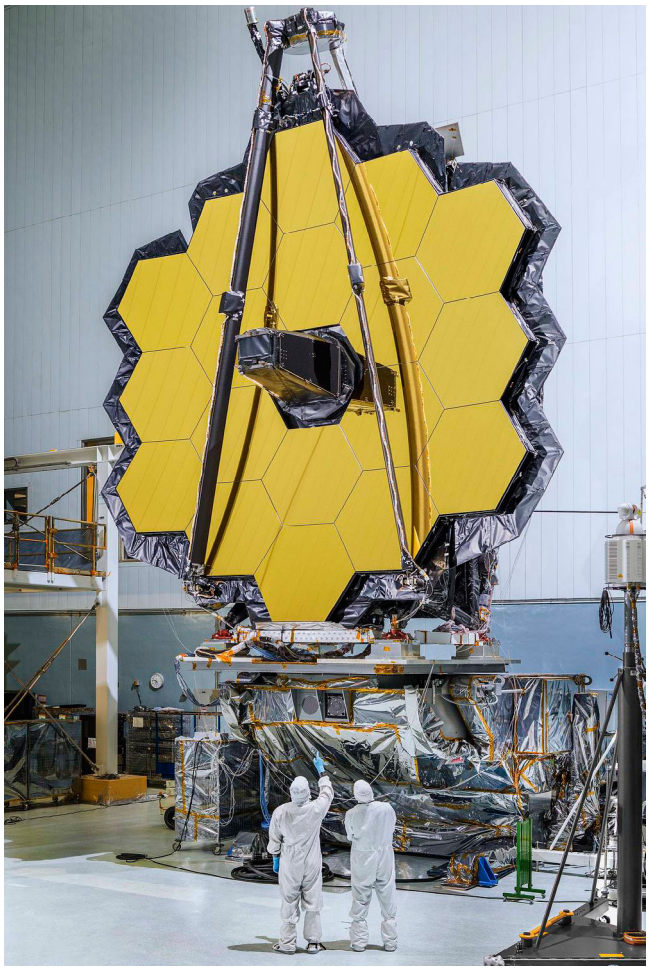

Figure 2. The James Webb Space Telescope completed optical telescope and integrated science instrument assembly in the clean room at NASA Goddard Space Flight Center in November 2016.[19]

[18] James Webb Space Telescope mission homepage at http://jwst.nasa.gov/
[19] Additional images at http://jwst.nasa.gov/.

8.2 Stratospheric Observatory for Infrared Astronomy

SOFIA[20], the world's largest airborne observatory, is a partnership with Deutsches Zentrum für Luft- und Raumfahrt (DLR), the German space agency. In 2015 and 2016, the first generation GREAT instrument was upgraded with new capabilities that greatly improved SOFIA's mapping capabilities in far-infrared line emission. Also in 2016, the first generation HAWC camera was upgraded with new detectors and a new capability to map polarization in the interstellar medium; science flights with this upgraded HAWC+ instrument will be underway in 2017. The HIRMES third generation mid- to far-infrared spectrometer was recently chosen for development and is scheduled for its first light flight in late 2019. A call for the fourth generation of SOFIA instrumentation is planned for mid-2017.

In 2015 and 2016, SOFIA has been in routine operations, achieving ~100 science flights per year and supporting ~70 GOs per year. Routine operations include an annual deployment to the southern hemisphere. The nominal five-year prime mission for SOFIA ends in 2019 and therefore SOFIA will be invited to the next Astrophysics Senior Review for mission extension.

8.3 X-ray Astronomy Recovery Mission

The JAXA-led ASTRO-H mission was launched on February 17, 2016, and renamed Hitomi. During commissioning, Hitomi failed due to an onboard anomaly. The NASA contributed Soft X-ray Spectrometer (SXS) was operational at 50 mK during commissioning and conducted science observations of the Perseus Cluster as part of the commissioning program. The SXS's unprecedented spectral resolution revealed for the first time the small and large scale velocity structure of an X-ray cluster of galaxies.[21]

On June 14, 2016, JAXA announced its intention to study an X-ray Astronomy Recovery Mission (XARM) that would be a rebuild of the Hitomi mission. JAXA has asked NASA to consider participating in the mission with a rebuild of the same contribution as for Hitomi. NASA has agreed to consider this, based on the premise that the NASA instrument would be a build-to-print of the SXS instrument that was flown and demonstrated on Hitomi. JAXA has indicated a desire to begin development of XARM, if approved, in FY 2017. To that end, NASA began, in collaboration with JAXA, to develop a notional joint implementation plan for NASA participation in XARM. A decision on XARM is anticipated by early 2017.

8.4 Operating Missions

The NASA 2016 Astrophysics Senior Review was held during February and March of 2016. The following missions were reviewed:

- Chandra X-ray Observatory,
- Fermi Gamma-ray Space Telescope,
- Hubble Space Telescope,
- K2 mission using the Kepler Space Telescope,
- Nuclear Spectroscopic Telescope Array (NuSTAR),
- Spitzer Space Telescope,
- Swift Gamma-ray Burst Explorer, and
- X-ray Multi-Mirror Mission (XMM)-Newton (an ESA mission with U.S. participation).

[20] SOFIA mission homepage at https://www.sofia.usra.edu/.
[21] Hitomi collaboration (Nature, 2016) at http://www.nature.com/nature/journal/v535/n7610/full/nature18627.html.

As in the 2014 Astrophysics Senior Review, there were individualized panels for Hubble and Chandra separate from the main comparative panel. Both the Hubble and Chandra reviews were undertaken as incremental reviews from those held in 2014. The Call for Proposals and Charge[22] to the 2016 Astrophysics Senior Review panels was released on September 25, 2015.

The 2016 Astrophysics Senior Review panels found no scientific reason to discontinue or significantly reduce any of the missions under review and that the scientific value of the complete 2016 Astrophysics Senior Review portfolio is greater than the sum of its parts. The panels recommended that NASA continue all of these missions.

Based on the findings of the 2016 Astrophysics Senior Review, NASA decided that all eight missions are approved to continue operations through FY 2017 and FY 2018. In addition, (a) Chandra, Fermi, Hubble, NuSTAR, Swift, and XMM-Newton are directed to plan on a continuation through FY 2019 and FY 2020, subject to the findings of the 2018 Astrophysics Senior Review; (b) Kepler/K2 is approved to continue operations until its fuel is exhausted (anticipated before the end of FY 2019) and to then conduct an orderly project closeout; and (c) Spitzer is approved to continue operations until the James Webb Space Telescope has successfully completed commissioning in mid-FY 2019 and to then conduct an orderly project closeout.

The reports of the three Senior Review panels, and NASA's response to the three reports, are available at https://science.nasa.gov/astrophysics/2016-senior-review-operating-missions/.

8.5 LISA Pathfinder

LISA Pathfinder[23] is an ESA mission to test the technology required to detect gravitational waves in the range of 0.1 to 100 mHz. The mission has demonstrated critical technologies for future gravitational wave observatories in a space environment. These technologies include gravitational reference sensing, drag-free attitude control, and interferometry with free-falling mirrors. NASA provided the Disturbance Reduction System (DRS) experiment, which includes a set of micro-thrusters that control the spacecraft's position to within a millionth of a millimeter.

LISA Pathfinder was successfully launched on December 3, 2015, and, after a 6-month cruise to the Earth-Sun L1 point, has been operating successfully for its nominal 6 months of operations. ESA has extended the mission until May 2017. The NASA-provided DRS successfully met its science requirements, and its operations were extended by NASA through May 2017.

8.6 Missions in Development

8.6.1 Transiting Exoplanet Survey Satellite

The Transiting Exoplanets Survey Satellite (TESS)[24] is a MIDEX mission down-selected in April 2013. In a two-year survey of the solar neighborhood, TESS will discover thousands of exoplanets in orbit around bright, nearby stars. The baseline science mission will be 36 months in duration, consisting of 24 months of spacecraft operations and ground-based observations and 12 months of additional ground-based observations and data analysis.

[22] Senior Review Call for Proposals and Charge at http://science.nasa.gov/astrophysics/2016-senior-review-operating-missions/.
[23] ESA LISA Pathfinder mission homepage at http://sci.esa.int/lisa-pathfinder/.
[24] TESS mission homepage at https://tess.gsfc.nasa.gov/.

TESS was confirmed to proceed into the implementation phase in October 2014. The project held a successful Critical Design Review (CDR) in August 2015. During 2016, TESS was in the fabrication phase with payload and spacecraft components being manufactured and integrated.

TESS will complete fabrication, integration, and testing during 2017 and is currently working toward a December 2017 launch readiness date on a SpaceX Falcon 9 expendable launch vehicle. The launch readiness commitment date is no later than June 2018.

8.6.2 Neutron star Interior Composition Explorer

The Neutron star Interior Composition Explorer (NICER)[25] is an Explorer Mission of Opportunity down-selected in April 2013. NICER is an X-ray timing experiment that will operate externally on the International Space Station (ISS). In addition to its science mission, NICER will perform a navigation demonstration using pulsars as cosmic clocks via the Station Explorer for X-ray Timing and Navigation (SEXTANT) experiment.

The NICER instrument was delivered in early June 2016 to Kennedy Space Center (KSC) and is ready for launch. NICER held a successful Operations Readiness Review (ORR) on October 28, 2016. The launch readiness date is no earlier than March 2017 on a SpaceX Falcon 9 to the International Space Station.

8.6.3 Cosmic Ray Energetics and Mass

The Cosmic Ray Energetics and Mass payload (ISS-CREAM)[26] is planned for installation externally on the International Space Station (ISS). ISS-CREAM will measure the origin, acceleration, and propagation of cosmic rays in the Galaxy. ISS-CREAM has finished development and is currently in storage at the Kennedy Space Center waiting launch on a SpaceX Falcon 9 to the ISS no earlier than June 2017. ISS CREAM on-orbit science operations are currently planned for a minimum of 1 year with a goal of 3 years.

8.6.4 Euclid

Euclid[27] is an ESA M-class mission to study the geometry and nature of the dark universe, slated for launch in 2020. NASA is providing 16 state-of-the-art infrared detectors and four spare detectors for the Near Infrared Spectrometer and Photometer (NISP) instrument on Euclid. Delivery of flight-qualified detectors to ESA will begin in 2017.

In 2014, following an independent review, NASA approved the Infrared Processing and Analysis Center (IPAC) to implement a Euclid NASA Science Center at IPAC (ENSCI) to enhance the science return from the mission and to make Euclid data easily available to the entire U.S. science community.

[25] NICER mission homepage at https://heasarc.gsfc.nasa.gov/docs/nicer/.
[26] ISS-CREAM mission homepage at http://cosmicray.umd.edu/iss-cream/.
[27] NASA Euclid project homepage at http://euclid.caltech.edu/.

9. Planning for the 2020 Astrophysics Decadal Survey

NASA has started preparations for the 2020 Astronomy and Astrophysics Decadal Survey[28]. One of the tasks of the 2020 Decadal Survey Committee will be to survey the field and recommend priorities for the most important scientific and technical activities of the coming decade. The Decadal Survey Committee may choose to prioritize a portfolio of activities containing a mix of prioritized large and medium-size missions, or even a program of competed medium-size missions. To this end, NASA has started studies for both large (cost exceeds $1B) and medium-size (cost in the range $400M to $1B) mission concepts.

9.1 Large Strategic Mission Concept Studies

The 2020 Astrophysics Decadal Survey will identify and prioritize large strategic missions to follow the James Webb Space Telescope and WFIRST. Starting in January 2015, NASA charged the Astrophysics community, through the Program Analysis Groups (PAGs) and the NASA Advisory Council's Astrophysics Subcommittee, to identify a small number of candidate large mission concepts, drawing from the concepts outlined in the NASA Astrophysics Visionary Roadmap, *Enduring Quests, Daring Visions*[29]. Four candidate mission concepts were identified through this process: the Far-Infrared Surveyor (renamed the Origins Space Telescope)[30], the Large Ultra Violet/Optical/Infrared Surveyor (LUVOIR)[31], the Habitable Exoplanet Imaging Mission (HabEx)[32], and the X-Ray Surveyor[33].

NASA formed four Science and Technology Definition Teams (STDTs), each led by two community chairs, to develop preliminary design reference missions (DRMs) for delivery to the 2020 Astrophysics Decadal Survey. Each study is assigned to a NASA Center for execution; LUVOIR and Origins Space Telescope are assigned to Goddard Space Flight Center (GSFC), Habitable Exoplanet Imaging Mission is assigned to Jet Propulsion Laboratory (JPL), and X-ray Surveyor is assigned to Marshall Space Flight Center (MSFC). A management plan[34] for these large mission concept studies was developed by NASA, including a schedule for deliverables from the teams.

9.2 Astrophysics Probes Studies

As part of the preparations for the 2020 Decadal Survey, NASA issued a solicitation on August 15, 2016, for proposals for mission concept studies for medium-size missions, also called Astrophysics Probes. Astrophysics Probes are envisioned to have a total mission cost between a MIDEX mission (~$400M) and a large strategic mission ($1B).

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[28] NASA 2020 Decadal Survey planning homepage at http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/.
[29] *Enduring Quests, Daring Visions* (NASA, December 2013), https://science.nasa.gov/astrophysics/documents/.
[30] Origins Space Telescope (Far-Infrared Surveyor) study homepage at http://asd.gsfc.nasa.gov/firs/.
[31] Large Ultraviolet/Optical/Infrared Surveyor study homepage at http://asd.gsfc.nasa.gov/luvoir/.
[32] *Habitable Exoplanet Imaging Mission study homepage* at http://www.jpl.nasa.gov/habex/.
[33] X-ray Surveyor study homepage at http://wwwastro.msfc.nasa.gov/xrs/.
[34] *See Management Plan for Large Mission Concept Studies* at http://science.nasa.gov/astrophysics/2020-decadal-survey-planning/.

Following peer review of the proposed concept studies, NASA will select a small number of proposed mission concepts for 18-month funded studies. NASA will provide mission design lab runs at a NASA Center and independent cost assessments for the selected mission concept studies. The selected study teams will deliver written reports in September 2018, which NASA will convey to the 2020 Decadal Survey.

Figure 3. Astrophysics missions as of December 2016.

10. Summary

This Update provides a summary, as of December 2016, of events and developments since the publication of the *Astrophysics Implementation Plan: 2014 Update* in December 2014 that affect NASA's strategy and progress for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

As recognized by the Midterm Assessment, NASA has made substantial progress in implementing the recommendations of the 2010 Decadal Survey and providing an overall balanced program. The Webb telescope remains on schedule and within budget for a launch in October 2018. WFIRST entered formulation in February 2016 and is being prepared for launch in the mid-2020s. The notional planning budget for NASA Astrophysics provided in the FY 2017 President's 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 Athena, an ESA-led advanced X-ray observatory that addresses many of the science objectives of International X-ray Observatory (IXO) that are discussed in the 2010 Decadal Survey. ESA and NASA are discussing the U.S. role in the ESA-led L3 gravitational wave observatory that addresses many of the science objectives of the Laser Interferometer Space Antenna (LISA) that are discussed in the 2010 Decadal Survey.

NASA is carrying out mission concept studies and technology development that will inform the 2020 Astrophysics Decadal Survey.

Acronyms

ADAP	Astrophysics Data Analysis Program
AO	Announcement of Opportunity
APRA	Astrophysics Research and Analysis
CDR	Critical Design Review
CMB	Cosmic Microwave Background
CGI	Coronagraph Instrument (on WFIRST)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DOE	Department of Energy
DRM	Design Reference Mission
DRS	Disturbance Reduction System (on LISA Pathfinder)
ENSCI	Euclid NASA Science Center at IPAC
EPDS	Extreme Precision Doppler Spectrometer (on WIYN Telescope)
ESA	European Space Agency
FSWG	Formulation Science Working Group
FY	Fiscal Year
GO	Guest Observer
GREAT	German Receiver for Astronomy at Terahertz Frequencies (on SOFIA)
GSFC	Goddard Space Flight Center
HabEx	Habitable Exoplanet Imaging Mission
HAWC	High-resolution Airborne Wideband Camera (on SOFIA)
HIRMES	High Resolution Mid-Infrared Spectrometer (on SOFIA)
IPAC	Infrared Processing and Analysis Center
ISS	International Space Station
IXO	International X-ray Observatory
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KDP	Key Decision Point
KSC	Kennedy Space Center
L2	Large Mission 2 in the ESA Cosmic Vision Programme
L3	Large Mission 3 in the ESA Cosmic Vision Programme
L3ST	L3 Study Team
LBTI	Large Binocular Telescope Interferometer
LISA	Laser Interferometer Space Antenna
LUVOIR	Large Ultraviolet/Optical/Infrared Surveyor
MCR	Mission Concept Review
MIDEX	Medium-class Explorer
MO	Mission of Opportunity
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NICER	Neutron star Interior Composition Explorer
NISP	Near Infrared Spectrometer and Photometer (on Euclid)
NOAO	National Optical Astronomy Observatories
NRC	National Research Council
NSF	National Science Foundation

NWNH	*New Worlds, New Horizons in Astronomy and Astrophysics*
NuSTAR	Nuclear Spectroscopic Telescope Array
ORR	Operational Readiness Review
PAG	Program Analysis Group
R&A	Research & Analysis
RFI	Request for Information
ROSES	Research Opportunities in Space and Earth Sciences
SAT	Strategic Astrophysics Technology
SEXTANT	Station Explorer for X-ray Timing and Navigation
SIT	Science Investigation Team
SMEX	Small Explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SRB	Standing Review Board
SRR	System Requirements Review
SST	Science Study Team
STDT	Science and Technology Definition Team
SWG	Science Working Group
SXS	Soft X-ray Spectrometer (on ASTRO-H/Hitomi)
TCAN	Theoretical and Computational Astrophysics Networks
TESS	Transiting Exoplanet Survey Satellite
WFI	Wide Field Imager (on Athena)
WFI	Wide Field Instrument (on WFIRST)
WFIRST	Wide-Field Infrared Survey Telescope
XARM	X-Ray Astronomy Recovery Mission
X-IFU	X-ray Integral Field Unit (on Athena)
XRP	Exoplanet Research Program