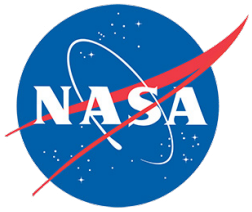
National Aeronautics and Space Administration



Astrophysics Implementation Plan: 2014 Update

This Update provides a summary since the publication of the *Astrophysics Implementation Plan* in December 2012 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 December 2012 *Astrophysics Implementation Plan*, which will not be revised.

Astrophysics Division
Science Mission Directorate
NASA Headquarters

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Revision 1: typographical errors corrected 12/18/14
Revision 2: typographical errors corrected 01/07/15

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1. Introduction and Purpose

This Update provides a summary since the publication of the *Astrophysics Implementation Plan*[1] in December 2012 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 December 2012 *Astrophysics Implementation Plan*, which will not be revised.

[1] *Astrophysics Implementation Plan* (December 2012); http://science.nasa.gov/astrophysics/documents/.
[2] *New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2010), http://www.nap.edu/catalog.php?record_id=12951.

2. Summary of Changes since December 2012

NASA has made substantial progress in implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*, hereafter the "Decadal Survey." Some of the important accomplishments 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*[3], remains on schedule and within budget for a launch in October 2018. See Section 8.1.
- Preformulation for the Wide-Field Infrared Survey Telescope (WFIRST) using the Astrophysics Focused Telescope Assets (AFTA) is well underway with support from both the Administration and the Congress. WFIRST is the highest priority large space mission of the Decadal Survey. The NASA Administrator has approved the Astrophysics Division to continue working on a WFIRST design that uses the AFTA telescope assets. The Congress appropriated funds in FY 2014 for WFIRST/AFTA preformulation and, in response to a request by the Administration in the FY 2015 President's Budget[4] Request, the Congress has appropriated additional funds in FY 2015 for the preformulation of WFIRST/AFTA[5]. An ad hoc National Research Council (NRC) study, *Evaluation of the Implementation of WFIRST in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*[6], found that the WFIRST/AFTA mission design is responsive to the Decadal Survey's recommendation for a WFIRST mission. See Section 4.
- The notional planning budget for NASA Astrophysics provided in the FY 2015 President's Budget Request accommodates an increase in the cadence of Astrophysics Explorers Program Announcements of Opportunity (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. An increased cadence for Astrophysics Explorers missions is the second highest priority large mission recommendation in the Decadal Survey. In addition to completing the Explorer projects currently under development [Soft X-ray Spectrometer (SXS) for the Japanese Aerospace Exploration Agency (JAXA) ASTRO-H mission, Neutron Star Interior Composition Explorer (NICER), Transiting Exoplanet Survey Satellite (TESS)], the planning budget supports a Small Explorer (SMEX) AO in late CY 2014, a Medium-class Explorer (MIDEX) AO approximately 2–3 years later, and alternating SMEX and MIDEX AOs every 2–3 years. See Section 5.

[3] *Astronomy and Astropysics in the New Millennium* (NRC, 2001), http://www.nap.edu/catalog.php?record_id=9839.
[4] FY 2015 President's Budget Request for NASA, http://www.nasa.gov/news/budget/.
[5] *Evaluation of the Implementation of WFIRST in the Context of New Worlds, New Horizons in Astronomy and Astrophysics* (NRC, 2014), http://www.nap.edu/catalog.php?record_id=18712.
[6] *New Worlds, New Horizons in Astronomy and Astrophysics*, http://www.nap.edu/catalog.php?record_id=12951.

- One of the prioritized large space missions of the Decadal Survey is an International X-ray Observatory (IXO). The European Space Agency (ESA) has announced that the second large mission in the Cosmic Vision Programme will be Athena, an advanced X-ray observatory to be launched in 2028. ESA, NASA, and JAXA have begun planning for Athena with the appointment of a Science Study Team (SST) in July 2014. ESA and NASA are discussing a NASA contribution to the mission. See Section 6.2.
- One of the prioritized large space missions of the Decadal Survey is the Laser Interferometer Space Antenna (LISA). ESA has announced that the third large mission in the Cosmic Vision Programme will be a space-based gravitational wave observatory to be launched in 2034. ESA and NASA are discussing a NASA contribution to the mission, and NASA is participating in ESA's technology review activities in 2014–2015. See Section 6.1.

Large-scale 1: WFIRST	Preformulation and focused technology development for WFIRST/AFTA (a 2.4m version of WFIRST with a coronagraph) are underway to enable a possible new start NET FY 2017.
Large-Scale 2. Augmentation to Explorer Program	Astrophysics Explorers planned budget increased to ~$160M/ year by FY 2016; supports decadal cadence of AOs, including AO for SMEX AO in Fall 2014 (FY 2015) and MIDEX AO in ~FY 2017.
Large-Scale 3. LISA	Strategic Astrophysics Technology (SAT) investments including LISA Pathfinder plus discussing partnership on ESA's L3 gravitational wave observatory.
Large-Scale 4. IXO	SAT investments plus pursuing partnership on ESA's L2 Athena X-ray observatory.
Medium-Scale 1. New Worlds Technology Development Program	Focused technology development for a coronagraph on WFIRST, SAT investments, and exoplanet probe mission concept studies; precursor science with ground-based investigations.
Medium-Scale 2. Inflation Probe Technology Development Program	Multiple balloon-borne investigations plus SAT investments.
Small-Scale. Research Program Augmentations	Increased annual R&A budget from $74M (FY 2010) to $82M (FY 2012 and beyond). Within R&A: established Theoretical and Computational Astrophysics Networks (TCAN) program with NSF; funding available for astrophysics theory; funding available for lab astrophysics; funding available for suborbital payloads.
Small-Scale. Intermediate Technology Development Augmentation	Continued competed SAT program element; directed technology funding for WFIRST and other decadal priorities; investments by NASA's Space Technology Mission Directorate (STMD).
Small-Scale. Future Ultraviolet-Visible Space Capability	SAT investments; STMD investments.
Small-Scale. SPICA (U.S. contributions to JAXA-led)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity.

Table 1. Recommended space activities of the Decadal Survey supported by the FY2014 NASA Appropriation, the FY2015 President's Budget Request, and its notional out years

3. Strategic Planning for NASA Astrophysics

In March 2014, NASA released the *NASA 2014 Strategic Plan*[7]. The first Strategic Goal is *"Expand the frontiers of knowledge, capability, and opportunity in space."* In support of this Strategic Goal, Strategic Objective 1.6 is to *"Discover how the universe works, explore how it began and evolved, and search for life on planets around other stars."* The NASA Astrophysics Division leads the Agency in addressing this strategic objective.

The NASA Science Mission Directorate (SMD) has developed a plan for addressing the strategic goals and objectives of the *NASA 2014 Strategic Plan*. The *NASA 2014 Science Plan*[8] focuses on changes to the program planned for 2014–2018. In addition to articulating SMD's principles, strategies, and challenges for implementing NASA's science program, the *NASA 2014 Science Plan* provides detailed plans for advancing NASA Astrophysics objectives.

With substantial input from the astrophysics community, the NASA Advisory Council's (NAC's) Astrophysics Subcommittee has developed *Enduring Quests, Daring Visions*[9], an astrophysics visionary roadmap to examine possible futures of the discipline in the longer term. This roadmap presents a science-driven 30-year vision for the future of NASA Astrophysics to describe research programs and missions that build on recent progress toward the science priorities of the Decadal Survey.

[7] *NASA 2014 Strategic Plan* (March 2014), http://www.nasa.gov/news/budget/.
[8] *NASA 2014 Science Plan* (April 2014), http://science.nasa.gov/about-us/science-strategy/.
[9] *Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades* (December 2013), http://science.nasa.gov/astrophysics/documents/.

4. Wide-Field Infrared Survey Telescope

Since Fall 2012, NASA has been studying potential uses of the 2.4m Astrophysics Focused Telescope Assets (AFTA) that were made available to the Agency by the National Reconnaissance Office (NRO). In May 2013, the WFIRST/AFTA Science Definition Team (SDT) produced a study report[10] concluding that for approximately the same costs, the telescope assets would enable a WFIRST mission with significantly improved science capabilities relative to the design described in the Decadal Survey. Furthermore, the larger aperture permits the addition of an exoplanet direct imaging coronagraph to WFIRST that would enable imaging and characterization of planets around nearby stars up to a decade earlier than contemplated in the Decadal Survey. The NASA Administrator therefore approved SMD in May 2013 to continue pre-formulation activities for the WFIRST/AFTA mission to prepare for a formal new start decision.

The WFIRST/AFTA SDT also produced a primer on the mission in May 2013, W*FIRST-2.4: What Every Astronomer Should Know*[11].

In July 2013, the WFIRST/AFTA SDT was re-chartered to carry mission pre-formulation through to January 2015, including development of a Design Reference Mission (DRM) with draft mission science requirements enabled by a strawman payload. For purposes of the study, carried out with the WFIRST/AFTA Study Office, the WFIRST/AFTA strawman payload is comprised of a wide-field infrared survey camera and a coronagraphic instrument. The WFIRST/AFTA SDT includes *ex officio* members provided by the space agencies of Canada, Japan, Europe, and Korea.

In December 2013, following several months of intense maturation, NASA selected the coronagraphic technologies for the mission to be a hybrid Lyot/shaped pupil design with a backup of a phase induced amplitude apodization design[12]. Significant technology investment is being made to advance these coronagraphic technologies, with milestones every several months to track progress. The Astrophysics Division has partnered with the NASA Space Technology Mission Directorate (STMD) to co-fund the maturation of the coronagraph technologies for flight. Additionally, a robust technology development effort is underway for the infrared detector arrays used in the wide-field instrument. Testing is ongoing on the existing telescope and its structural elements to validate its readiness for flight in its WFIRST/AFTA application.

NASA commissioned the NRC to assess the responsiveness of the WFIRST/AFTA mission concept, both with and without the coronagraph, to the recommendations of the Decadal Survey. The NRC March 2014 report, *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*, lauds the additional science WFIRST/AFTA could obtain, while cautioning that the approach with new technologies, especially for the coronagraph, carries risk for cost and schedule growth that should be mitigated aggressively. NASA has accelerated the technology development investment beginning in FY 2014 with more than $50M of funding provided for this purpose specifically identified by Congress. Technology development plans have been drafted to continue these efforts to achieve a sufficient technology readiness level for all WFIRST/AFTA elements by the end of FY 2016; achieving these plans is dependent on the amount of funding appropriated for WFIRST/AFTA preformulation in the years following FY 2014.

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[10] *Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA) Final Report* by the Science Definition Team (SDT) and WFIRST Project (May 2013), http://wfirst.gsfc.nasa.gov/.
[11] *WFIRST-2.4: What Every Astronomer Should Know* (May 2013), http://wfirst.gsfc.nasa.gov/; http://arxiv.org/abs/1305.5425.
[12] "HQ Direction on AFTA FY14 Coronagraph Technology Investment" (December 2013), http://wfirst.gsfc.nasa.gov/.

In April 2014, an interim report of the SDT and Study Office was released providing the status of the concept and its technology development activities[13]. A new ROSES program element, WFIRST Preparatory Science (WPS), was initiated to support efforts to bridge from basic theory to observational modeling for WFIRST/AFTA, further augmenting the science definition of the mission[14].

Continuing this momentum, the FY 2015 President's Budget Request contains for the first time an explicit line item for the above activities, to fund the "*ongoing study of a possible WFIRST/AFTA mission, the next major observatory beyond JWST, for a potential start of formulation activities later this decade*." The FY 2015 Omnibus appropriations bills includes additional funding *"for NASA to proceed with further risk reduction and detailed formulation on a science mission that meets the exoplanet and dark energy science objectives of WFIRST."*

Figure 1 shows a summary timeline of the major milestones of the WFIRST/AFTA mission development.

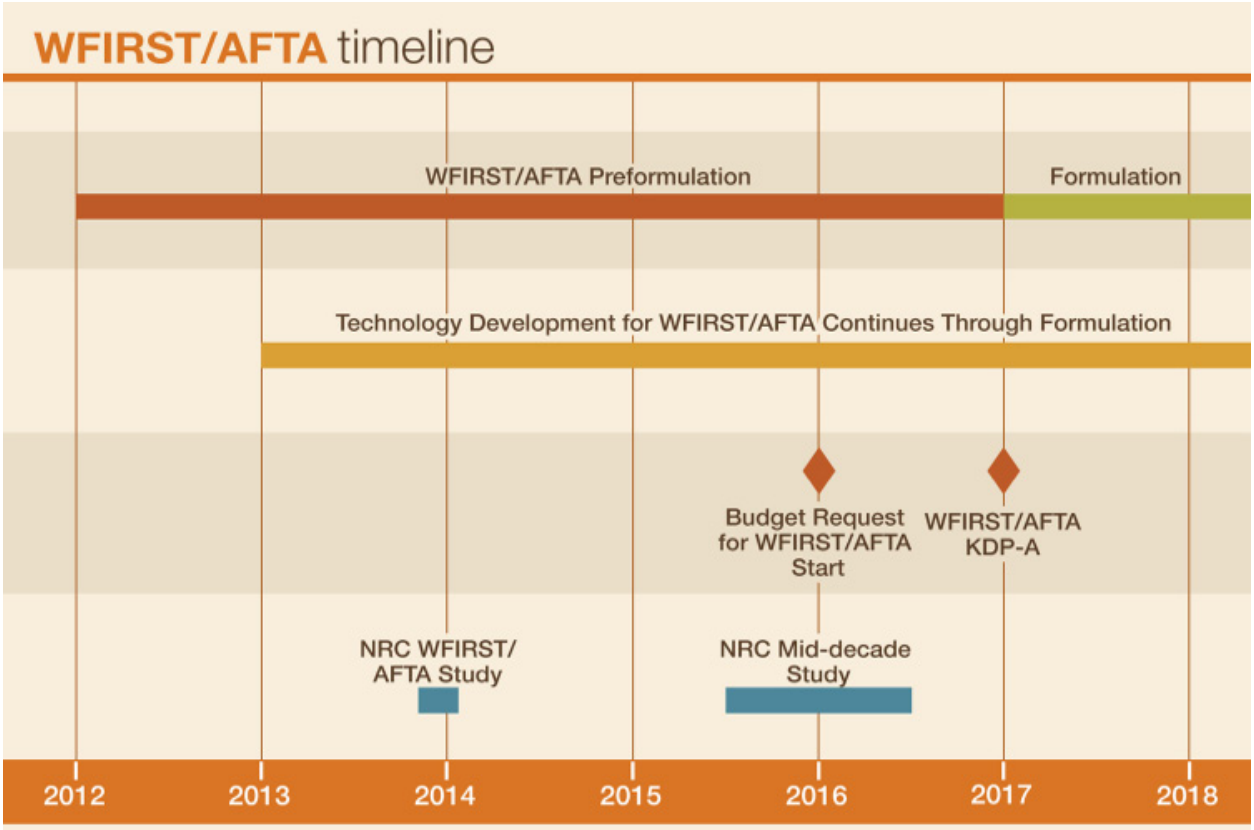

Figure 1. Summary of the major milestones of t he WFIRST/AFTA mission development; all dates are approximate and are shown to the nearest year.

[13] *WFIRST-AFTA Science Definition Team Interim Report* (April 2013), http://wfirst.gsfc.nasa.gov/.
[14] WFIRST Preparatory Science, Appendix D.10 of ROSES-2014, http://solicitation.nasaprs.com/ROSES2014.

5. Astrophysics Explorers

Two new missions, the Transiting Exoplanet Survey Satellite (TESS), a Small Explorer, and the Neutron star Interior Composition Explorer (NICER), a Mission of Opportunity – were downselected in Spring 2013 and confirmed for implementation in 2014. See Section 8.3.

The planning budget for the Astrophysics Explorers Program has been augmented in response to the Decadal Survey recommendation to enable rapid response to science opportunities by selecting, through Announcements of Opportunity (AOs) two Small Explorer (SMEX) missions, two Medium-class Explorer (MIDEX) missions, and four Missions of Opportunity (MO) within a decade.

An AO for a SMEX and a MO has been released in Fall 2014[15]. An AO for a MIDEX and a MO is planned for ~2016/2017 (FY 2017), and subsequent AOs, each for a mission and a MO, are anticipated every 2–3 years

[15] Astrophysics Explorers 2014 AO information page, http://explorers.larc.nasa.gov/APSMEX/.

6. Other Decadal Survey Large-Scale Prioritized Activities

The Decadal Survey recommended technology development leading to international partnerships for a space-based gravitational wave observatory and an international X-ray observatory. The Decadal Survey described the science goals of these missions as well as a notional implementation in the form of the LISA and IXO missions, both of which required substantive partnerships with non-U.S. space agencies. Although the missions are not being implemented in the notional manner described in the Decadal Survey, due to a changed budget landscape and other international events, NASA is making progress addressing the relevant science priorities in partnership with ESA.

6.1 Gravitational Wave Observatory

In the Fall of 2013, the ESA Senior Survey Committee recommended "The Gravitational Universe" science theme for its Cosmic Vision Programme third large (L3) mission, with a launch in 2034. This recommendation was endorsed by the ESA Science Programme Committee in November 2013. NASA has expressed an interest in collaborating with ESA for a future L3 gravitational wave observatory.

ESA has formed a study group to provide guidance on the overall feasibility of a space-based gravitational wave observatory. The study group, named Gravitational Observatory Advisory Team (GOAT)[16], includes participation from the U.S. as well as ex officio members from NASA and JAXA.

6.2 Advanced X-ray Observatory

In the Fall of 2013, the ESA Senior Survey Committee recommended "The Hot and Energetic Universe" science theme for its Cosmic Vision Programme second large (L2) mission. This recommendation was endorsed by the ESA Science Programme Committee in November 2013. In June 2014, ESA selected the Advanced Telescope for High Energy Astrophysics[17] (Athena) as the mission concept to fulfill this theme. NASA is discussing a partnership with ESA on the Athena mission, including contributions to the payload and/or mission hardware. The form of the NASA contribution to the Athena mission is a subject of discussion between NASA and ESA as the mission architecture is formulated in advance of the ESA AO for nationally funded mission elements, which is planned to be issued by ESA in 2015. The X-ray Science Interest Group (XRSIG) of the Physics of the Cosmos Program Analysis Group (PhysPAG) produced a list of items that span a broad financial and scientific range.

The NASA participation in the Athena mission is responsive to the Decadal Survey prioritization of the International X-ray Observatory (IXO) and its science, and to the Decadal Survey recommendation to engage in international collaboration at a range of scales, i.e. to "*consider a wide range of approaches to realize participation in international projects and to provide access for the U.S. astronomy and astrophysics community to a larger suite of facilities than can be supported within the United States*."[18]

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[16] ESA Gravitational Observatory Advisory Team home page, http://www.cosmos.esa.int/web/GOAT.
[17] ESA Athena website, http://www.cosmos.esa.int/web/athena/.
[18] *New Worlds, New Horizons in Astronomy and Astrophysics*, ibid, page 27.

ESA has 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, which began in July 2014 and will run for ~2 years. 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. With the agreement of ESA, the Athena SST is establishing a working group structure to be 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.

In July 2013, NASA formed a Science and Technology Definition Team (STDT) to formulate a mission concept for an X-ray Astrophysics Probe (XAP)[19]. The XAP STDT met in October 2013. By then, ESA had announced selection of the "Hot and Energetic Universe" as the main theme of its L2 mission to be addressed by an X-ray Observatory led by ESA with possible international participation. In view of a possible NASA contribution to the L2 Athena mission, the XAP STDT was terminated in October 2013.

[19] X-ray Probe Study, http://pcos.gsfc.nasa.gov/studies/x-ray-probe-2013-2014.php.

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

The Decadal Survey prioritized two technology development programs as medium-scale activities. The first is a New Worlds Technology Development Program, including precursor science activities, preparing for an exoplanet-imaging mission beyond 2020. The second is an Inflation Probe Technology Development Program, developing technology for studying the Cosmic Microwave Background (CMB) and the epoch of inflation in preparation for a possible mission beyond 2020.

7.1 New Worlds Technology Development Program

In January 2013, NASA issued a call for membership in two Science and Technology Definition Teams (STDTs) for direct imaging of exoplanets, via probe-scale missions (each less than one billion dollars life cycle cost), which would serve as backup options for WFIRST. The two STDTs are focused on studies of missions including coronagraph and starshade systems, respectively. Teams were selected in May 2013, with 10 scientists each. With engineering input from comparable-size groups at JPL, the teams submitted Interim Reports in April 2014[20] and plan to submit Final Reports in January 2015.

New technology for strategic exoplanet missions has been supported through the competed APRA and SAT programs, as well as the WFIRST/AFTA coronagraph directed technology development program. The technology development for a coronagraph leading to a potential demonstration instrument on WFIRST/AFTA is under way with co-funding from STMD (see Section 4). To date, more than 30 awards have been made for tasks that advance the technology readiness of external occulters (starshades), coronagraphs, and their associated supporting technologies. These projects are supported through testing and metrology infrastructure investments, and all results are validated through a rigorous peer review program. The starlight suppression technology development under way, including the technologies being developed for a potential WFIRST/AFTA coronagraph, respond to the Decadal Survey recommendation that "candidate starlight suppression techniques … should be developed to a level such that mission definition for a space-based planet imaging and spectroscopy mission could start late in the decade … ."[21]

The Decadal Survey recommends 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 imaging and spectroscopy mission"[22]. In Fall 2014, the NASA Astrophysics Division and the NSF Astronomical Sciences Division undertook a joint exoplanet initiative. The WIYN telescope on Kitt Peak, through the National Optical Astronomy Observatories (NOAO) share of the partnership, is the preferred host for a joint exoplanet program that ultimately will focus on the high precision measurement of radial velocities. The program, as currently envisioned, would be carried out in two stages:

- In 2015–2018, (a) conduct an exoplanet-targeted general observer program with existing instrumentation on WIYN using the NOAO share of WIYN time while (b) developing a NASA-funded Extreme Precision Doppler Spectrometer (EPDS) for ground-based follow-up studies for the TESS mission as well as JWST precursor science.
- In 2018–2022, begin using EPDS to conduct an exoplanet-targeted program at WIYN with the EPDS instrument using the NOAO share of WIYN time.

[20] Exoplanet Probe Science and Technology Definition Teams home page, http://exep.jpl.nasa.gov/stdt/.
[21] *New Worlds, New Horizons in Astronomy and Astrophysics*, ibid, page 216.
[22] *New Worlds, New Horizons in Astronomy and Astrophysics*, ibid, page 20

A NASA solicitation for the EPDS instrument is planned for early CY 2015.

The Large Binocular Telescope Interferometer (LBTI) will use its nulling mode to measure the mid-infrared flux due to circumstellar dust ("exozodi") around 50 nearby stars, with 1-sigma sensitivity per star of 3–6 zodi. These measurements will translate into estimates of the mid-infrared and visible brightness due to exozodi dust in the habitable zones of the target stars. Knowledge of the exozodi levels likely to be encountered around typical nearby stars is needed input to the optimum design of a future space mission to detect and characterize exo-Earths.

Precursor science activities necessary for a future exoplanet imaging mission are supported through the Exoplanet Research Program (XRP, formerly known as the Origins of Solar Systems or OSS program), which is co-sponsored by the SMD Planetary Science Division.

7.2 Inflation Probe Technology Development Program

The Astrophysics Division is supporting three CMB polarization balloon missions. Multiple flights have occurred or are planned, beginning in December 2012 and continuing for the next 5 years. If successful, initial results are expected to be released in 2015 from multiple teams, with more robust results being released in the following years.

The APRA program is also supporting CMB polarization technology development, particularly those that exploit superconducting and kinetic materials and techniques. With advances in detectors, polarized input coupling methods, multiplexing readouts, and coatings and filters, near photon noise-limited detector arrays with thousands of elements have been fabricated for testing and use in these CMB polarization suborbital missions, and as technology readiness demonstrators for an Inflation Probe. In addition, data reduction and analysis techniques are also being developed and tested.

7.3 Research and Analysis

After a 10% increase for Research and Analysis (R&A) in FY2012, funding for the research award programs has been maintained at this higher level in subsequent years. The FY 2015 President's Budget Request maintains this higher level, with a further 7% increase projected in the nominal runout for FY 2016.

Six networks were selected in FY2013 for funding under the Theory and Computational Astrophysics Networks (TCAN) program, run jointly with the NSF Astronomical Sciences Division.

7.4 Future Ultraviolet/Visible/Far-Infrared Space Capability

The presentations and requirement analyses of the ultraviolet/visible mission concept submissions discussed in the September 2012 workshop were captured in a refereed paper for general access and distribution to the community[23]. On-going investments in APRA, SAT, and through STMD collaborations are advancing the maturity of technologies identified as needed for future missions within this portfolio. Through FY 2014, eleven SAT investigations have been selected and funded. Five of them are dedicated to ultraviolet/visible detector technologies, two for optical coatings, two for large normal incidence optics, and four represent developments in far-IR detector technologies. Furthermore, in collaboration with STMD, two investigations were funded by the STMD Early Stage Innovation (ESI) program on the topic of "thin-film physics or optical coatings."

[23] "Scientific objectives for UV/visible astrophysics investigations: a summary of responses by the community," http://arxiv.org/abs/1306.0553.

8. Other Activities within Astrophysics

The presentations and requirement analyses of the ultraviolet/visible mission concept submissions discussed in the September 2012 workshop were captured in a refereed paper for general access and distribution to the community[24]. On-going investments in APRA, SAT, and through STMD collaborations are advancing the maturity of technologies identified as needed for future missions within this portfolio. Through FY 2014, eleven SAT investigations have been selected and funded. Five of them are dedicated to ultraviolet/visible detector technologies, two for optical coatings, two for large normal incidence optics, and four represent developments in far-IR detector technologies. Furthermore, in collaboration with STMD, two investigations were funded by the STMD Early Stage Innovation (ESI) program on the topic of "thin-film physics or optical coatings."

8.1 James Webb Space Telescope

The James Webb Space Telescope (JWST)[25] continues to make good progress toward meeting its planned launch date of October 2018. The complex, hundred-day Integrated Science Instrument Module (ISIM) cryovacuum test with all the science instruments was successfully conducted during 2014. The project also completed the pathfinder telescope backplane and successfully integrated the pathfinder mirror units.

8.2 Stratospheric Observatory for Infrared Astronomy

The Stratospheric Observatory for Infrared Astronomy (SOFIA)[26] is the largest airborne observatory in the world, dedicated to the study of the Universe at infrared wavelengths. NASA and the German Aerospace Center, DLR, together operate SOFIA, a Boeing 747SP aircraft modified to accommodate a 2.5 meter gyro-stabilized telescope. SOFIA provides a platform for infusion of advanced instrument technologies. During 2015, SOFIA will conduct first flights with two second-generation instruments: a German multi-pixel far-infrared heterodyne receiver system and an advanced U.S. detector in a far-infrared imaging polarimeter system.

In March 2014, the FY2 015 President's Budget Request proposed placing SOFIA into storage in the event additional partners could not be found to replace the U.S. contribution to the mission. FY 2014 operations continued while the Congress conducted the appropriations process. These operations included the execution of Cycle 2 science observations, the continuation of Science Instrument commissioning, and a Heavy Maintenance Visit in Germany from June to November 2014. Upon completion of commissioning flights for a fourth instrument, SOFIA entered the KDP-E review process, which concluded on May 29, 2014, when SOFIA was declared operational. All six first-generation instruments have now flown on the observatory. The FY 2015 Omnibus appropriations bill continues funding for SOFIA in FY 2015 at a reduced level.

The NASA Office of Inspector General (OIG) completed an audit of the SOFIA Program on July 9, 2014. NASA is working to respond to each of the OIG's ten recommendations[27].

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[24] "Scientific objectives for UV/visible astrophysics investigations: a summary of responses by the community," http://arxiv.org/abs/1306.0553.
[25] JWST website, http://jwst.nasa.gov/.
[26] SOFIA website, http://www.sofia.usra.edu/.
[27] *NASA Office of Inspector General audit of SOFIA: NASA's Stratospheric Observatory for Infrared Astronomy*, http://oig.nasa.gov/audits/reports/FY14/IG-14-022.pdf.

8.3 Missions in Development

8.3.1 *ASTRO-H*

ASTRO-H[28] is a JAXA-led facility-class X-ray astrophysics mission. NASA is providing flight hardware to JAXA for the Soft X-Ray Spectrometer instrument. All U.S. provided flight hardware has been delivered to Japan and integrated for performance testing. The launch readiness date is targeted for November 2015 on a Japanese H-IIA launch vehicle.

8.3.2 *Euclid*

Euclid[29] is an ESA-led M-class mission to study the geometry and nature of the dark Universe, slated for launch in 2020. In January 2013, following an ad hoc NRC study, *Assessment of a Plan for U.S. Participation in Euclid*[30], NASA joined the mission. NASA will contribute 16 state-of-the-art infrared detectors and four spare detectors for one of two science instruments on Euclid. In addition, NASA was asked by ESA to provide U.S. representation on the Euclid Consortium, an international body of more than 1,000 members who will oversee development of the instruments, manage science operations, and analyze data. Following an open call for proposals to participate on the Euclid Consortium, NASA nominated three U.S. science teams in 2013 for the Euclid Consortium. In 2014, 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.

8.3.3 *LISA Pathfinder*

LISA Pathfinder[31] is an ESA mission to test the technology required to detect gravitational waves in the range of 0.1 to 100 mHz. The mission will demonstrate 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 is providing the Disturbance Reduction System (DRS) experiment, which includes a set of micro-thrusters that will control the spacecraft's position to within a millionth of a millimeter. LISA Pathfinder is on track for launch no earlier than July 2015. LISA Pathfinder's operational phase will last six months after it reaches its final operational orbit around the first Sun-Earth Lagrange point.

8.3.4 *Neutron star Interior Composition Explorer*

The Neutron star Interior Composition Explorer (NICER) is an Explorer Mission of Opportunity downselected in April 2013. NICER is an X-ray timing experiment that will operate 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. NICER/SEXTANT is funded jointly by SMD and STMD. NICER was confirmed to proceed into the implementation phase in February 2014. The launch readiness date is no later than February 2017 on a Space-X Falcon 9 to the International Space Station.

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[28] NASA ASTRO-H project website, http://heasarc.gsfc.nasa.gov/docs/astroh/.
[29] NASA Euclid project website, http://euclid.caltech.edu/.
[30] "*Assessment of a Plan for U.S. Participation in Euclid* (NRC, 2012), http://www.nap.edu/catalog/13357/assessment-of-a-plan-for-us-participation-in-euclid.
[31] ESA LISA Pathfinder website, http://www.esa.int/Our_Activities/Space_Science/LISA_Pathfinder_overview.

8.3.5 *Transiting Exoplanets Survey Satellite*

The Transiting Exoplanets Survey Satellite (TESS) is a Medium-class Explorer downselected in April 2013. In a 2-year survey of the solar neighborhood, TESS will discover thousands of exoplanets in orbit around the brightest stars in the sky. The baseline science mission will be 36 months in duration, and will consist of 24 months of spacecraft operations and ground-based observations and 12 months of additional ground-based observations and data analysis. TESS was confirmed to proceed into the implementation phase in October 2014. The launch readiness date is no later than June 2018 on an expendable launch vehicle.

8.4 Missions in Operation

The 2014 Senior Review was conducted March 10–April 3, 2014.

For the first time, there were individualized panels for Hubble and Chandra separate from the main comparative panel. The Hubble panel found that Hubble is operating at or near the highest level of performance and scientific productivity in its history, and, if appropriately funded, the Hubble observatory will in all likelihood continue at its present level of achievement and productivity for years to come. The Chandra panel found that there are no obstacles to Chandra's continuing scientific productivity, and that Chandra discoveries continue to have an extraordinarily high impact on the understanding of our universe.

The report of the Senior Review panel[32] makes it clear that all of the projects proposing within the 2014 Senior Review are scientifically meritorious and deserving of continued funding and continued operations. The panel recommended that additional funding be found to preserve the portfolio of operating missions. Unfortunately, the current constrained budget conditions makes it difficult for NASA to increase funding for operating missions without unacceptable impacts on other parts of the astrophysics program.

NASA used the prioritized rankings and individual recommendations of the Senior Review to make the following decisions for each of the projects in the Senior Review. The missions are presented in alphabetical order.

- Chandra X-ray Observatory: extension approved
- Fermi Gamma-ray Space telescope: extension approved
- Hubble Space Telescope: extension approved
- Kepler Space Telescope: K2 mission approved
- Nuclear Spectroscopic Telescope Array (NuSTAR): extension approved
- Planck (ESA mission): data analysis augmentation approved
- Spitzer Space Telescope: extension approved
- Suzaku/Astro-E2 (JAXA mission): extension approved
- Swift Gamma-ray Burst Explorer: extension approved
- Wide-field Infrared Survey Explorer (WISE): data-analysis augmentation not approved
- X-ray Multi-Mirror Mission-Newton (ESA mission): extension approved

[32] *Reports of the 2014 Senior Review Panels*, http://science.nasa.gov/astrophysics/2014-senior-review-operating-missions/.

Figure 2 provides a summary of the Astrophysics Division's mission portfolio following the 2014 Senior Review. The next Senior Review will be held in Spring 2016.

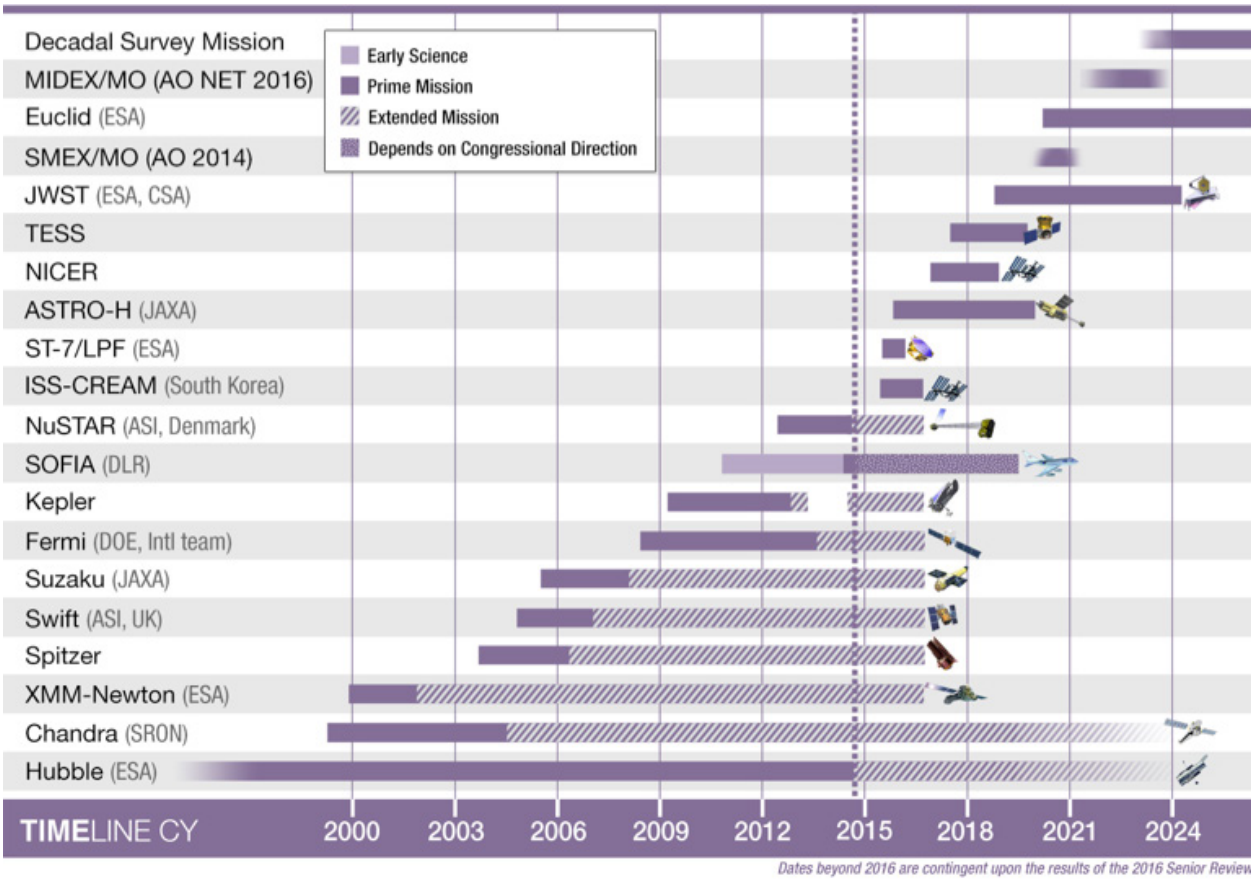

Figure 2. Summary of the Astrophysics Division's mission portfolio following the 2014 Senior Review. It does not include missions for which non-archival data analysis is still ongoing (Herschel, Planck) or operated by other organizations (NEO-WISE).

9. Planning for the Astrophysics Decadal Survey in 2020

The NRC will conduct a mid-decade review for NASA, NSF, and the Department of Energy (DOE) starting in 2015 and finishing in 2016. The purpose of the mid-decade review is to assess the Agencies' progress and plans against the recommendations and priorities of the Decadal Survey within the budget constraints facing the Agencies.

The next Astrophysics Decadal Survey in 2020 will identify and prioritize large missions to follow JWST and WFIRST/AFTA. In the second half of the present decade, NASA plans to conduct preliminary studies of candidate large missions to provide input to the 2020 Astrophysics Decadal Survey prioritization process. Community input, through the Program Analysis Groups (PAGs) and the NAC's Astrophysics Subcommittee, will be used to identify a small number of candidate large mission concepts. Large mission concepts drawn from the *New Worlds, New Horizons in Astronomy and Astrophysics* Decadal Survey, from the *NASA 2014 Science Plan*, and from the *Enduring Quests, Daring Visions* Roadmap will provide the starting point for this input. The Astrophysics Division will set up science and technology definition teams (STDTs) for each mission concept, and each study will be assigned to a NASA Center for execution, with the goal to develop design reference missions (DRMs) for delivery to the 2020 Astrophysics Decadal Survey committee.

No decision has been made by NASA at this time on how to provide input to the 2020 Astrophysics Decadal Survey Committee regarding probe-class missions.

10. Summary

This Update provides a summary as of December 2014 of events and developments since the publication of the *Astrophysics Implementation Plan* in December 2012 that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

NASA has made substantial progress in implementing the Decadal Survey. JWST remains on schedule and within budget for a launch in October 2018. Preformulation for the WFIRST/AFTA is well underway with support from both the Administration and the Congress. The notional planning budget for NASA Astrophysics provided in the FY 2015 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.

ESA and NASA are discussing a NASA contribution to Athena, an ESA-led advanced X-ray observatory that addresses many of the science objectives of IXO. Similarly, ESA and NASA are conducting a science and technology assessment for an ESA-led gravitational wave observatory that addresses many of the science objectives of LISA.

NASA has begun planning for mission concept studies and technology development that will inform the 2020 Astrophysics Decadal Survey.

Acronyms

AFTA	Astrophysics Focused Telescope Assets
AO	Announcement of Opportunity
APRA	Astronomy and Physics Research and Analysis
Athena	Advanced Telescope for High Energy Astrophysics
BPA	Board on Physics and Astronomy
CMB	Cosmic Microwave Background
CY	Calendar Year
DLR	Deutschen Zentrums für Luft und Raumfahrt (German Aerospace Center)
DOE	Department of Energy
DRM	Design reference Mission
DRS	Disturbance Reduction System
ENSCI	Euclid NASA Science Center at IPAC
EPDS	Extreme Precision Doppler Spectrometer
ESA	European Space Agency
ESI	Early Stage Innovation
FY	Fiscal Year
GOAT	Gravitational Observatory Advisory Team
IPAC	Infrared Processing and Analysis Center
IR	Infrared
ISIM	Integrated Science Instrument Module
ISS	International Space Station
IXO	International X-ray Observatory
JAXA	Japanese Space Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KDP	Key Decision Point
L2	Large mission 2 (ESA's)
L3	Large mission 3 (ESA's)
LBTI	Large Binocular Telescope Interferometer
LISA	Laser Interferometer Space Antenna
MIDEX	Medium-class Explorer
MIRI	Mid Infrared Instrument MO Mission of Opportunity
MO	Mission of Opportunity
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NET	Not Earlier Than
NICER	Neutron star Interior Composition Explorer
NOAO	National Optical Astronomy Observatories
NRC	National Research Council
NRO	National Reconnaissance Office
NSF	National Science Foundation
NWNH	New Worlds, New Horizons (the Decadal Survey)
NuSTAR	Nuclear Spectroscopic Telescope Array
OIG	Office of Inspector General
OSS	Origins of the Solar System

PAG	Program Analysis Group
PhysPAG	Physics of the Cosmos Program Analysis Group
R&A	Research & Analysis
ROSES	Research Opportunities in Space and Earth Sciences
SAT	Strategic Astrophysics Technology
SDT	Science Definition Team
SEXTANT	Station Explorer for X-Ray Timing and Navigation
SMD	Science Mission Directorate
SMEX	Small-class Explorer
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPICA	Space Infrared Telescope for Cosmology and Astrophysics
SST	Science Study Team
STDT	Science and Technology Definition Team
STMD	Space Technology Mission Directorate
SXS	Soft X-ray Spectrometer
TCAN	Theory and Computational Networks program
TESS	Transiting Exoplanet Survey Satellite
WFIRST	Wide Field Infrared Survey Telescope
WISE	Wide-field Infrared Survey Explorer
WIYN	Wisconsin-Indiana-Yale-NOAO
WPS	WFIRST Preparatory Science
XAP	X-ray Astrophysics Probe
XMM	X-ray Multi-Mirror Mission.
XRP	Exoplanet Research Program
XRSIG	X-ray Science Interest Group

References

NRC Reports:

Assessment of a Plan for U.S. Participation in Euclid (NRC, 2012)	http://www.nap.edu/catalog.php?record_id=13357
Astronomy and Astrophysics in the New Millennium (NRC, 2001)	http://www.nap.edu/catalog.php?record_id=9839
Evaluation of the Implementation of WFIRST in the Context of New Worlds, New Horizons in Astronomy and Astrophysics (NRC, 2014)	http://www.nap.edu/catalog.php?record_id=18717
New Worlds, New Horizons in Astronomy and Astrophysics (NRC, 2010)	http://www.nap.edu/catalog.php?record_id=12951

NASA Websites and Documents:

Astrophysics Explorers 2014 AO information page	http://explorers.larc.nasa.gov/APSMEX/
Astrophysics Implementation Plan (December 2012)	http://science.nasa.gov/astrophysics/documents/
Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades	http://science.nasa.gov/astrophysics/documents/
Exoplanet Probe Science and Technology Definition Teams home page	http://exep.jpl.nasa.gov/stdt/
FY 2015 President's Budget Request for NASA	http://www.nasa.gov/news/budget/#.VImrL0hgP2V
"HQ Direction on AFTA FY14 Coronagraph Technology Investment" (December 2013)	http://wfirst.gsfc.nasa.gov/
JWST website	http://jwst.nasa.gov/
NASA 2014 Science Plan (April 2014)	http://science.nasa.gov/about-us/science-strategy/
NASA 2014 Strategic Plan (March 2014)	http://www.nasa.gov/news/budget/
NASA ASTRO-H project website	http://heasarc.gsfc.nasa.gov/docs/astroh/
NASA Euclid project website	http://euclid.caltech.edu/
NASA Office of Inspector General audit of SOFIA: NASA's Stratospheric Observatory for Infrared Astronomy	http://oig.nasa.gov/audits/reports/FY14/IG-14-022.pdf

Reports of the 2014 Senior Review Panels	http://science.nasa.gov/astrophysics/2014-senior-review-operating-missions/
"Scientific objectives for UV/visible astrophysics investigations: a summary of responses by the community"	http://arxiv.org/abs/1306.0553
WFIRST-2.4: What Every Astronomer Should Know (May 2013)	http://arxiv.org/abs/1305.5425
WFIRST-AFTA Science Definition Team Interim Report (April 2013)	http://wfirst.gsfc.nasa.gov
"WFIRST Preparatory Science," Appendix D.10 of ROSES-2014	http://solicitation.nasaprs.com/ROSES2014
Wide-Field Infrared Survey Telescope - Astrophysics Focused Telescope Assets (WFIRST-AFTA) Final Report by the Science Definition Team (SDT) and WFIRST Project (May 2013)	http://wfirst.gsfc.nasa.gov
X-ray Probe Study	http://pcos.gsfc.nasa.gov/studies/x-ray-probe-2013-2014.php

ESA Websites and Documents:

ESA Athena website	http://www.cosmos.esa.int/web/athena/
ESA Gravitational Observatory Advisory Team home page	http://www.cosmos.esa.int/web/GOAT
ESA LISA Pathfinder website	http://www.esa.int/Our_Activities/Space_Science/LISA_Pathfinder_overview