2016 Hubble Space Telescope Senior Review

8-10 March, 2016

PANEL

Chair: Robert Milkey (American Astronomical Society, retired)

Taft Armandroff (McDonald Observatory)

Jay Gallagher (University of Wisconsin Madison)

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FINAL REPORT DELIVERED TO

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2016 Hubble Space Telescope Senior Review

EXECUTIVE SUMMARY

The Hubble Space Telescope remains the most productive single telescope in the world, with over 800 peer-reviewed papers based on Hubble data published each year. Barring major system failures, it should continue to do so for a number of years to come. System failures due to aging hardware are, however, becoming more likely and strategic planning for the 'sunset years' of the Hubble mission should start.

A summary of the Panel responses to each element of its charges (in *italics*) follows:

1. *Consider the PMOs described in the 2016 Senior Review proposal, and assess the scientific merit and expected science return of the observatory over the next 2 to 4 years.*
   While the Prioritized Mission Objectives (PMOs) listed in the 2016 proposal are demonstrations of the scientific capabilities of the HST mission for which success can be readily measured, a limited set of PMOs is not representative of the full scope of science possible with a mission that is driven largely by proposals from the research community. The panel appreciates that five of the nine PMOs listed are community-enabling. However, the panel recommends developing higher-level PMOs for the next review to more fully represent the scope of science available to the user community.

2. *Assess the observatory's progress made toward achieving the PMOs described in the 2014 Senior Review proposal. A copy of the proposal will be made available to reviewers.*
   Excellent progress has been made on the PMOs from the 2014 proposal. Most of these were challenging scientific projects and were expected to take several years to fully complete.

The panel will also consider (a) the response of the observatory to any findings made of the 2014 Senior Review, (b) any additional operational changes implemented by the observatory since 2014, (c) any further operational changes planned over the next 2 to 4 years, and (d) the observatory's identification of risks to the science program over the next 2 to 4 years. Focusing principally on these areas, and using the 2014 Senior Review report as a baseline, the panel will provide updates on:

3. *The efficiency of the observatory, and its associated operations center and infrastructure in enabling new science, archival research, and theory.*

   The overall scientific output of the observatory and its associated archive remain very high, enabling the accomplishment of forefront science. Additionally, innovative approaches to maximizing the output for those HST observing capabilities, which will vanish when HST ceases to operate, promise optimal use of these in HST's final years.

4. *The efficiency of the science and mission operations processes, and identify any obvious technical obstacles to achieving the observatory's science objectives in the next two to four years.*

   In recent years the efficiency of the observing has been improved, while at the same time the resources necessary for these operations have decreased. The project has also proactively assessed the likely risks to operations or efficiency resulting from failures of spacecraft systems or instruments and has been preparing responses to these.

5. *The overall quality of observatory stewardship, and the usage of the allocated funds, in light of overall limited financial resources, to maximize science quality, observational efficiency, and return on investment.*

   The overall stewardship of the observatory by NASA is excellent, as exemplified by continuing efforts to improving total output, including the maintenance of the user grants program. In an environment of level real dollar funding it will be a continuing challenge for all elements of the project to accommodate a decrease in purchasing power. It is especially important to maintain an adequate level of funding in the General Observer/Archival Researcher (GO/AR) grants program to enable the timely reduction and analysis of HST data.

6. *Relevant findings that would enhance the science return of the mission within its available resources.*

   a. The 2016 panel examined the findings of the 2014 Senior Review and concluded that overall those findings remain applicable to the HST mission.

   b. Despite the inability to forecast the lifetime of HST, it is appropriate to study options to maximize the science return from the remaining lifetime of this extremely productive observatory. This includes the optimizing both tools and funding for the utilization of HST data.

   c. The panel was unable to evaluate whether the program has optimally balanced its resource portfolio given the provided material. It recommends that the Project develop a strategic plan that provides linkage between resource allocations, staffing levels, risk posture, dependencies on other components of the Project, and scientific goals and productivity metrics.

   d. The IRAF packages, on which the tool kit for the analysis of HST data has been based, is reaching the end of its lifetime and STScI is addressing this critical issue.

2016 Hubble Space Telescope Senior Review

INTRODUCTION

The Senior Review panel for the Hubble Space Telescope (HST) met at the Space Telescope Science Institute (STScI) on March 8 through 10, 2016. At the outset the charge to the panel was presented by Dr. Paul Hertz, Director of the Astrophysics Division at NASA Headquarters. During the remainder meeting the panel was provided considerable written documentation as well as ample opportunity to interact with both the management team from the Hubble Project Office at the Goddard Space flight Center (GSFC) and the management and staff from STScI. The panel members wish to express their gratitude for the degree and candor of these interactions.

Throughout the deliberations, the panel was amply supported by Drs. Jeffrey Hayes, Program Executive and Daniel Evans, Program Scientist, from the Astrophysics Division at NASA Headquarters.

The panel is also appreciative of the logistical support provided by the staff of NASA Research & Education Support Services.

FINDINGS

This section is organized in response to NASA's charge to the Senior Review panel. The elements of the charge are in **bold** with the panel's findings below.

Consistent with NASA's response to the 2014 Senior Review, the 2016 SR will be an incremental or "delta" review that will focus on changes since the 2014 SR with an emphasis on the efficiencies of both missions. Accordingly, the panel will:

1. **Consider the PMOs described in the 2016 Senior Review proposal, and assess the scientific merit and expected science return of the observatory over the next 2 to 4 years.**
   The high priority scientific Prioritized Mission Objectives (PMOs) listed in Table 1.3 (See Appendix A, from the Senior Review proposal) represent clear examples of initiatives that demonstrate the scope and high quality of the current scientific capabilities of the HST mission. These four points are discussed in more detail in Section 2 of the proposal:

   The Senior Review panel recognizes that science with HST is largely driven by proposals from the community. The selected high priority science PMOs therefore naturally cover only a small fraction of HST's scientific footprint. These programs, however, are representative of unique HST capabilities applied to addressing scientifically important issues. Progress updates for the 2016 proposal science PMOs should be reported to the next Senior Review in more detail than was provided for the 2014 science PMOs.

   It might be more effective to select Scientific PMOs at a higher level for any future delta Senior Review. For example, the UV initiative, short time scale proposals, and very large proposals represent significant changes aimed at improving the scientific output from HST. The panel welcomes these types of initiatives and would appreciate learning how they work out.

A second set of “new community enabling” PMOs also are included in Table 1.3. These are additional research tools for HST that have come to the HST Project via interactions with the community. The Senior Review panel appreciates the addition of these PMOs as examples of the continuing engagement between HST and its researchers to enhance the scientific return from this mature mission. For example, the desire for better spectroscopic archives and full image mosaics have clear scientific value and will further increase the value of the archives for research. That these initiatives were chosen to have a good cost-benefit ratio is also a plus.

A minor point, however, concerns how these community enabling tasks were selected to have high priority. A clearer explanation of the ways in which the community comments, which the panel understands come via a number of formal and informal channels, are folded into the priorities would be useful for future reviews. In particular the panel was interested in obtaining deeper insights into how the high priority community enabling PMOs fit within a 2-4 year strategic vision for the HST project.

2. **Assess the observatory’s progress made toward achieving the PMOs described in the 2014 Senior Review proposal. A copy of the proposal will be made available to reviewers.**

   Ten PMOs were outlined in the 2014 proposal, covering all areas of astrophysics from the solar system to cosmology. Highlights include measuring the Hubble constant to 2.4% (with the ultimate goal of 1%) using the recently developed WF3 scanning mode, and the discovery of 27 high redshift Type Ia supernovae. Work continues on the Frontier Fields: two fields remain to be observed but the program has already resulted in an impressive list of publications, including the detection of a galaxy at $z \approx 11$. The PHAT survey team has made excellent progress on data reduction, and are now addressing a wide range of issues such as metallicity and dust distributions. Hubble is making important contributions to the new and rapidly evolving field of exoplanet atmospheres and played a key role in the continued success of the New Horizons Spacecraft by identifying a post-Kuiper belt target. The first version of the Hubble Source Catalog has been published. While the proposal was not as explicit as it could have been in describing the degree of completion on each of the PMOs, with the additional discussions provided through the site visit, the panel concludes that excellent progress has been made on the ten PMOs from 2014, demonstrating once again that Hubble continues to produce cutting edge science (see Appendix B for details).

The panel will also consider (a) the response of the observatory to any findings made of the 2014 Senior Review, (b) any additional operational changes implemented by the observatory since 2014, (c) any further operational changes planned over the next 2 to 4 years, and (d) the observatory’s identification of risks to the science program over the next 2 to 4 years. Focusing principally on these areas, and using the 2014 Senior Review report as a baseline, the panel will provide updates on:

3. **The efficiency of the observatory, and its associated operations center and infrastructure in enabling new science, archival research, and theory.**
   The Hubble Space Telescope remains the most productive single telescope in the world, with over 800 peer-reviewed papers based on Hubble data published each year. The quality of the publications (as traced by the citations) strongly demonstrate the high efficiency of the observatory in enabling new science.

   The science (STScI) and spacecraft (GSFC) operation centers have demonstrated a robust collaborative relationship through their coordinated development of novel, innovative observing modes for the aging observatory. One example is the support of the UV initiative through the additional calibration of the UV-capable instruments, and finessing a technique for that enables high contrast imaging for studies of circumstellar disks.   A new spatial scanning mode for WFC3 was implemented which provided parallax measurements with accuracies of 20-40 micro-arcseconds, a significant improvement over previous measurements using the same detector. These improved measurements helps tighten the error in the Hubble constant from 3.3% to a projected 1.8% by 2017, which in turn provides considerable value to cosmology and offers intriguing potential implications.

In addition, the observatory continues to explore ways to enhance the utility of the proposal process to obtain scientific data with HST. Recently the program introduced a mid-cycle proposal option for small observing program. In the upcoming cycle it also will offer the option for very large projects. This diversity of proposal styles help to ensure that HST can respond to new discoveries while also providing complete data sets to support GO and archival research.

The HST data archive continues to demonstrate its scientific legacy by motivating at least half of all the papers using HST data that are published each year. The science center is to be commended for taking advantage of the expertise amongst its staff in developing new tools and data products that will further enhance the usability of the archive. The opportunity to make such improvements would likely be lost once the inevitable but unscheduled end-of-mission is realized. The new archive tools currently being developed include a user interface with expanded search capabilities and data products that combine archived data into products that facilitate scientific research (e.g., mosaiced images and co-added spectra).

4. **The efficiency of the science and mission operations processes, and identify any obvious technical obstacles to achieving the observatory's science objectives in the next two to four years.**
The operational changes implemented in the past two years have either reduced staffing dedicated to operations without impact on the science achieved or been new initiatives designed to maximize the science return of Hubble in its mature years. Special attention is being paid to the unique capabilities of HST as well as the advantages of large programs and the flexibility provided by mid-cycle call. Additionally, significant improvements in observing efficiency have been obtained over the past several years with the current observing efficiency of around 50%, approaching the maximum that can be achieved given the restrictions of low earth orbit, very slow slew speed and other complications resulting from the mission design. It is important to remember that the early-mission goal for observing efficiency was 35% and that the current improvements have been accomplished while reducing the staff required for the planning and scheduling activities.

The project has evaluated the known potential risks to observatory operations in some detail and has been preparing extensive contingency plans for responding to these. For those failures that have the highest risk, *e.g*., gyro failure, they have even begun to prepare operating modes to minimize the impact of these on the conduct of HST science. The panel believes that the HST project's response in this area is exemplary and the 25 year history of observatory operations provides significant data with which to evaluate these mitigation strategies. The pre-planning and preparation of ground and flight software options for the most likely failures that is underway will minimize the loss of observing time or observing efficiency should these occur.

5. **The overall quality of observatory stewardship, and the usage of the allocated funds, in light of overall limited financial resources, to maximize science quality, observational efficiency, and return on investment.**

The overall stewardship of the Hubble observatory remains excellent. The three-way split of the allocated funds (to mission operations at GSFC, to science operations at STScI, and to the grants program) continues to be an effective way to maximize science quality and observational efficiency.

The panel commends in particular the Senior Project Scientist for providing an effective link between the GSFC and STScI parts of the mission.

The GSFC mission operation responded constructively to the 2014 Senior Review and reduced staffing while dedicating efforts to lifetime extension measures, as well as identifying risk to the mission operations. The Mission Operations at GSFC was slightly restructured, retaining expertise and staffing to respond rapidly to anomalies in operations - which is appropriate at this stage of the mission. The current goal is to overlap at least one year with the JWST mission (longer if possible) and the current staffing is adequate to do so. The panel was particularly pleased to see comprehensive analysis on the risks and lifetime extension measures (e.g., changes in the FGS use, improvements of the pointing control), and work addressing the sustainability of the operations, as well as mitigating obsolescence issues (e.g., planning for various scenarios around gyro failures and strategies to maximize Hubble's performance for several more years).

STScI is to be commended for remaining open to innovation and changes in science operations after 25 years of operation. They continue to adapt science operations to community needs, in view of maximizing the science quality and observational efficiency in the remaining years in the Hubble mission. Science operations continuously analyzes the best use of HST, as the end of life of the observatory approaches and in view of an overlap with JWST. They adapted their PMOs and the overall resource allocation to respond to the large fraction of archival use of the Hubble data (*e.g.*, listing five 'community enabling' PMOs, see section 1 above). They continued to introduced and support new observing modes (*e.g.*, the UV initiative, mid-cycle proposals, very large programs). They further increased the scheduling efficiency by a few percent to now near maximum. The staff voluntary turnover is low at STScI (<4%), which reflects a healthy, satisfied workforce. STScI is managing well the transition to the JWST era.

The panel welcomes the effort to maintain a constant level of GO/AR grants over the years. GO/AR grants have been and will continue to be critical to maximize the scientific return of the Hubble mission (even after its formal end-of-life). However, costs at universities have increased due to inflation, rising overheads and tuition. These costs have increased at a higher rate than the federal inflation rate, resulting in a reduced buying power for GO/AR grants. The panel suggests that STScI convene a task force to examine and quantify the impact of reduced purchasing power has on GO grants, and the implications for science productivity. The task force should also look at the balance of resources as Hubble enters the final phase of the mission.

6. **Relevant findings that would enhance the science return of the mission within its available resources.**

The 2016 Senior Review panel considers many findings of the 2014 review to continue to be applicable, and others have new caveats as the Mission faces challenges associated with end-of-life transitioning. Below is a point-by-point review of the 2016 Senior Review panel findings with respect to those of the 2014 panel, with the 2014 panel's findings in italics:

1. Hubble remains a critical facility in advancing our knowledge of the cosmos. Hubble continues to expand the frontiers of astronomy and astrophysics and addresses the strategic objectives of the Decadal Review and the Astrophysics Division Roadmap.

This statement is as true in 2016 as it was in 2014, and Hubble continues to make significant contributions toward the objectives of the Decadal Review and the Astrophysics Division Roadmap.

2. Hubble is currently at or near its peak in terms of scientific impact, data quality and productivity. It is returning exceptional value to the U.S. taxpayer for the dollars invested and is likely to continue doing so for the foreseeable future. We see the continuation of HST for the next few years at its present level of capability as a highly cost effective investment in NASA's astrophysics portfolio.

This statement remains as valid as in the previous report and will continue to remain so, barring major observatory degradation, for the foreseeable future. The 2016 Senior Review panel confirms that HST is continuing to provide excellent value to NASA and ESA.

3. New observing techniques and dramatic increases in calibration precision are enabling scientific investigations with Hubble that would have been inconceivable a decade ago. These include measurement of the Hubble constant to 1% precision and the associated determination of the dark energy density parameter, w; and the detection of water vapor in the atmospheres of transiting exoplanets.

This finding remains applicable. However, with the exception of a few observing modes, the 2016 panel does not expect the immediate future to bring the same dramatic improvements in precision that were achieved in the period following SM4 and preceding the 2014 report.

4. Demand for Hubble observing time by the global astronomical community continues at a very high level and it is expected to remain so for the foreseeable future.

While the demand for observing time fluctuates somewhat from cycle to cycle, the demand remains quite high and is reasonably balanced among the instruments. Additionally, a steady demand for archival data demonstrates the high value of the Hubble archive and indicates the need for long-term support, independent of the operational status of the Hubble spacecraft. Recent expansions of capability, which have significant potential for sustaining the growth of science productivity, are the provision of new data products, research-enabling archive tools and user interfaces, and new observational techniques and observing initiatives to get the most out of HST's aging instruments.

5. The Hubble spacecraft and its scientific instruments are in excellent operating condition, and are projected to function well for many years. The current suite of instruments is reaching its peak productivity.

> This finding remains true, but responding to changes in both spacecraft and instrument performance, whether abrupt failure or slow degradation will be a major challenge in the coming years. The project is aware of the various risks, analyzes the trends in instrument performance and is working on mitigation strategies.

6. Impressive improvements in operational cost efficiency were achieved during the "prime" phase of the post-SM4 mission. Operations manpower has been reduced to a level approximately one half of what it was a decade ago. Most notably the Space Telescope Control Center at Goddard has transitioned from full-time, 24/7 staffing, to a highly automated mode with 8/5 staffing, and the planning and scheduling functions at STScI have been similarly streamlined. The GSFC/STScI operations staff is to be commended for being responsive to budgetary pressures and maintaining the functionality and efficiency of a legacy ground system. We are confident that the project will continue to demonstrate excellent stewardship in pursuing additional efficiencies.

> This excellent and commendable effort on the part of the project continues to provide benefits. It will be necessary to continue to seek efficiencies to cope with the declining purchasing power under a flat budget. The panel believes that this is possible without impacting the scientific return too significantly. However the 2016 panel does not expect future improvements in cost efficiency to be as dramatic as those identified for the 2014 report, and some loss of capability may have to be accepted. See details below under "Additional Findings".

7. In the brief span of this review we were unable to determine reliably additional areas where efficiency could be significantly improved. Identification of any further reductions that would clearly not adversely affect scientific quality or productivity would require a more in-depth study. There seem to be some areas where continuous process improvement might be possible. We believe savings realized in this way are likely to be small.

> The project has responded by continuing to seek efficiencies and this has led to some additional savings in manpower, especially within the GSFC contingent, but also at STScI. This activity must be an ongoing process as the flat budget will continue to demand a slow reduction of costs in both groups. See related discussions below under "Additional Findings".

8. The scientific productivity of HST has been due not just to the remarkable capabilities of the observatory, but also to the consistent and adequate funding of the general observers and archival researchers. We believe the STScI has demonstrated good stewardship in administering this program. We applaud and strongly endorse the project's determination to maintain this precious resource. We would recommend that before any significant cuts to the GO/AR funding are contemplated, further attention be given to additional efficiencies throughout the program.

> The GO/AR funding remains well administered and looks to be stable in the coming years. Despite the flat overall budget for the mission, the panel recommends maintaining the purchasing power of the grants supporting the general and archival researchers.

9. HST is unique in its ability to inform and inspire the public about humanity's place in the universe. The committee is impressed by the important public engagement work that HST EPO has done over the years, and expresses its support that resources be programmed that allow that work to continue at STScI.

> The 2016 panel did not examine the activities of this group in detail but we have no reason to contradict the conclusions of the prior panel.

<u>Additional Findings of the 2016 Review:</u>

Another focus of the 2016 Senior Review panel was to evaluate the response of the Project to the following 2014 findings with regards to operational efficiencies: "*Some areas within the Hubble project were identified as places where the potential for further increase in efficiency could be investigated, but in these cases the following caveats apply. Given the short time that was available to the panel, we cannot guarantee that higher efficiencies could truly be realized in these areas, nor can we reliably evaluate what the impact on science would ultimately be if changes were made." (2014 Senior Review report).*

The review panel concentrated on key areas such as the degree to which the mission is operating at the full optimization afforded by HST's resources. This focus is considered to be particularly relevant, given the obligation to maximize science productivity in these "sunset years" of the mission and the need to be prepared to react to performance capability limitations in the observatory as components gradually degrade or catastrophically fail. Such optimization, for example, might come in the form of redistribution of resources within the HST portfolio, guided by risk analysis, short versus long-term prioritization, and community needs (such as grant funding levels). The ability to perform such optimization requires a full understanding of how resources are distributed across the main components of the project, as well as the inter-dependencies of the components (particularly with regards to expertise within the staff).

Within the mission operations area, the panel found the resource allocation, staff reduction implementation in targeted areas, and phasing plans as the mission takes advantage of automation and acceptable risk postures to be described in a transparent manner that was exceptionally responsive to the 2014 report.

Within the science operations area, the resource allocations and staff phasing plans, commensurate with where the mission currently is in its lifecycle, were not as clearly defined. In the absence of such details, the Senior Review panel was unable to fully evaluate if this component of the program is operating with an optimally balanced portfolio across the various elements it supports (including grant funding, science community outreach, development activities associated with the archive and science instrument operations, instrument and pipeline maintenance and operations). The panel recommends that the Project develop a strategic plan that provides linkage between resource allocations, staffing levels, risk posture, dependencies on other components of the Project, and scientific goals and productivity metrics. The Project can utilize the strategic plan as a tool for identifying areas which are not optimized as well as a blueprint for how to reallocate resources as capabilities degrade or are permanently lost as HST nears the end of its life. The panel recommends that a review of this strategic plan and its implementation be included in the next Senior Review.

In addition to the above concerns, the Senior Review panel suggests that the Project continues to seek opportunities for science enhancements as HST enters into its hopefully extended end of lifetime operational phase. These possible opportunities include, as discussed above, the potential to speed up the science return from new observations via modified approaches to GO funding. In this phase of the mission, close contact with the user community is essential; the HST Project is encouraged to redouble its efforts to obtain community comments and input on observatory priorities, as "democratized science" is even more important now.

The software tool kit for the analysis of data from HST historically is based on the well known IRAF packages, yet IRAF is nearing the end of its useful lifetime. STScI recognizes and is addressing this critical issue. Developing sustaining capabilities to replace those currently contained in IRAF, as well as new tools, is essential to both HST, JWST and future missions.

A twofold strategy therefore is in progress and supported by the panel:

1. IRAF should continue to be useful by running it on virtual machines. This information is being posted and plans exist to make this approach readily available to the community. It is expected that this fix will serve for a few years.

2. For a longer term solution STScI is in the process of building specialized software tools that will support future missions. These, however, are not planned to provide an integrated data reduction and analysis package that is equivalent to IRAF.

NASA should be aware that the demise of IRAF as a readily available integrated astronomical software toolkit can significantly impact the scientific productivity of its astrophysical missions. This issue thus needs to be explicitly addressed by STScI with strong input from the user community.

RECOMMENDATIONS FOR CONDUCT OF FUTURE REVIEWS

This panel has found that the "delta" review format has been both appropriate and useful in this cycle. Absent major changes in the spacecraft and instrument performance the panel concludes that the next Senior Review can also be a delta review. However, this panel feels that a delta review might be most efficient if it were structured to address specific points of concern so that material submitted in the project's proposal and the charge to the review panel can be optimally aligned. Science PMOs presented in a "delta" review should be at the highest level, to illustrate the responsible stewardship of the mission rather than to provide a full demonstration of the scientific capabilities of the mission.

For a long-term, community driven observatory such as Hubble, the choice between a "full" review and a "delta" review, *i.e.*, whether to pose the question of whether the scientific return from the mission warrants the resources assigned, should be determined more by changes in the mission than by any chronological cycle. In this respect there are two drivers that might trigger a full review of HST:

- A need to adopt a new mission funding level for coming years.
- A significant degradation in observatory capability or efficiency.

If either of these conditions prevail, then NASA may wish to direct a future panel to assess the whether the scientific capability of the observatory warrants the level of resources necessary to accommodate these changed conditions.

Appendix A

Table 1.3: High-priority Mission Science Objectives							
2014 Prioritized Mission Science Objectives and Number		**2016 Prioritized Mission Objectives**	**Hubble Strategic Objectives**		**NASA Objectives**		**Proposal Section**
			UV Initiative	JWST Prep Science	NASA SMD Science Plan	New Worlds, New Horizons	
	2016 Status: First Results	**New Community-driven Objectives**					
2.1 Measure Hubble Constant (H_0) to 1% precision	Published (2016)	Map galaxy formation at the cosmic dawn and high noon (2.3, 2.4)*		✔	A2	1	2.1
2.2 Characterize SN Ia evolution at $z > 1.5$ to constrain dark energy equation of state	Published (2014)	Map star formation and gas in the Milky Way and nearby galaxies (2.6, 2.9)*	✔	✔	A2	1	2.2
2.3 Map cluster dark matter and observe structure in high-redshift galaxies	Published (2014)	Explore the diversity of exoplanet atmospheres and their host stars (2.7)*	✔	✔	A3	2	2.3
2.4 Measure cosmic variance and galaxy evolution at high redshift	Published (2016)	Watch the dynamical and chemical evolution of the outer planets and their satellites (2.8)*	✔		A2 A3	2	2.4
2.5 Detect isolated, stellar-mass black holes	Initial results	**New Community-enabling Objectives**					
2.6 Map the star-formation history of M31	Published (2014)	Extend master catalog of sources observed by Hubble (2.10)*			A1 A2	3	2.5
2.7 Measure water vapor in exoplanet atmospheres	Published (2014)	Enhance spectroscopic science return of Hubble archives (2.10)*	✔		A1, A2	2	
2.8 Explore the solar system and find new constituents	Published (2014)	Create full-depth mosaics on all fields imaged by Hubble (2.10)*			A1, A2	2 3	
2.9 Explore circumgalactic and intergalactic environments	Published (2014)	Enable new archive queries through target-oriented access (2.10)*	✔		A1 A2	3	
2.10 Create a Hubble Source Catalog	Version 1 released	Expand science through mission support and joint programs (2.1–2.9)*	✔	✔	All	All	2.6

** Follows on from the numbered 2014 High-priority Mission Objectives.*

Appendix B

Measure Hubble Constant (H_0) to 1% Precision

Major Findings from 2014 to Present: Significant progress has been made towards a 1% Hubble constant, having lowered the error to 2.4% from the 10% of the HST Key Project (Freedman et al. 2001) and from the 3.3% reported in the 2014 Senior Review. Initial results show tension with Planck findings, and may indicate the need for additional physics beyond the traditional ΛCDM model if confirmed.

Status: In progress. Reaching 1% will require extended HST observations and the aid of Gaia parallaxes.

Notable Reference(s): Casertano et al. 2015 ApJ submitted, Riess et al. 2016 to be submitted

Characterize SN Ia evolution at z>1.5 to constrain dark energy equation of state

Major Findings from 2014 to Present: The CANDELS and CLASH Multi-cycle Treasury Programs have discovered 37 high redshift supernovae of type Ia; the low rate of SNe at z>1 hints at the rarity of prompt progenitors.

Status: In progress. Observations of high redshift supernovae with the Hubble Frontier Fields are still underway. Mock observations show that the sample of SNe is sufficient to improve the uncertainty in the w_a parameter σ_{wa} by up to 21%.

Notable Reference(s): Rodney et al. 2014 AJ 148, 18, Graur et al. 2014 ApJ 783, 28

Map cluster dark matter and observe structure in high-redshift galaxies

Major Findings from 2014 to Present: The largest sample of bright, high redshift galaxies to date have been identified as a result of Multi-Cycle Treasury Programs and follow-up GO programs. Lensed supernovae observed in the Hubble Frontier Fields are empirically testing cluster gravitational lens models, and cluster observations are providing the most stringent constraints on the dark matter equation of state.

Status: In progress. Hubble Frontier Fields observations are continuing, and will reach fainter galaxies to constrain the abundance of low-luminosity galaxies that may dominate the ionizing photon production.

Notable Reference(s): Schmidt et al. 2016 ApJ 818, 38, Kelly et al. 2015 Sci, 347, 1123, Sartoris et al. 2014 ApJ 783, L11

Measure cosmic variance and galaxy evolution at high redshift

Major Findings from 2014 to Present: Imaging data from previous Multi-Cycle Treasury Programs combined with spectroscopic follow-up have detected the currently known highest redshift galaxy, at z of 11.1. High redshift galaxies found in the Frontier Fields show that early galaxy evolution lasts long enough to explain cosmic reionization. Theoretical predictions for cosmic variance from Hubble Frontier Fields and Hubble Ultradeep Fields have been made.

Status: In progress. Multi-Cycle Treasury Program data continue to be mined for follow-up spectroscopic observations. Hubble Frontier Fields data collection is still in progress.

Notable Reference(s): Oesch et al. 2016 ApJ accepted, McLeod et al. 2015 MNRAS 450, 3032

Detect isolated, stellar-mass black holes

Major Findings from 2014 to Present: Measured astrometric shifts during a microlensing event, coupled with an independent distance determination, are sensitive down to 0.4 solar masses.

Status: Final analysis of one potentially isolated black hole is in progress and initial analysis of additional searches are consistent with the expected number of events.

Notable Reference: Sahu et al. in preparation

Map the star-formation history of M31

Major Findings from 2014 to Present: Observations of Andromeda through the PHAT Multi-Cycle Treasury program reveal variations in the star formation history on small spatial scales as well as galaxy-wide fluctuations, demonstrating that the global star formation rate has been constant over 500 MY. Results pave the way for extending studies to different galactic environments.

Status: Initial results on the star formation history of M31 have been obtained.

Notable Reference: Lewis et al. 2015 ApJ 805, 183

Measure water vapor in exoplanet atmospheres

Major Findings from 2014 to Present: Increasing precision of spectroscopic techniques enable larger numbers and types of exoplanets to be studied, extending beyond hot Jupiters to Neptune-sized exoplanets. Some exoplanets exhibit clear atmospheres with strong water detections while others show cloudy/hazy atmospheres, with weak spectral features.

Status: As the number of exoplanet transmission spectra increases into sample sizes of a few tens and more, this PMO has evolved from simple measurements of water vapor to understanding the systematics of exoplanet atmospheres, composition and dynamics.

Notable Reference: Sing et al. 2016 Nature 529, 59

Explore the solar system and find new constituents

Major Findings from 2014 to Present: Hubble observations were crucial to the success of the New Horizons mission to Pluto, ranging from identifying new moons to verifying spacecraft safety to identifying post-Pluto KBO target. Monitoring observations of the system reveal chaotic tumbling of two moons, demonstrating intricate satellite dynamics.

Status: New Horizons mission support finished. Mission support to NASA and ESA's planetary science missions continue as needed. OPAL program expands the time baseline and enhances the legacy value of previous Hubble monitoring of outer solar system observations.

Notable Reference: Showalter & Hamilton 2015 Nature 522, 45

Explore circumgalactic and intergalactic environments

Major Findings from 2014 to Present: The technique of absorption line spectroscopy has revealed previously unrecognized massive reservoirs for star formation and accretion in galactic haloes as well as enabling detailed observations of structures at the outskirts of the Milky Way galaxy. It is now widely accepted that the gas surrounding galaxies plays a major role in their formation and evolution.

Status: Large programs accepted in Cycles 22 and 23 are still in progress, so this strategic goal is still being pursued.

Notable Reference(s): Lehner et al. 2015 ApJ 804, 79, Fox et al. 2016 ApJ 816, L11

Create a Hubble Source Catalog

Major Findings from 2014 to Present: Version 1 of the Hubble Source Catalog was released in Feb. 2015, providing 80 million detections of 30 million sources, and lowering the barrier to science from the hundreds of millions of sources viewed by HST over its lifetime. From a recent archive survey, roughly 30% of users accessing the archive for Hubble data have also used the HSC, less than one year after initial roll-out.