2022 Astrophysics Senior Review

Senior Review Subcommittee Report

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Executive Summary

The Senior Review Subcommittee evaluated nine missions: eight within the Astrophysics Division (APD) portfolio, and one mission from the Planetary Sciences Division (PSD) portfolio proposing a set of astrophysics experiments in an extended mission phase. These missions enable the full suite of astrophysical study from the large-scale distribution of dark and baryonic matter down to the detailed nature of individual stellar or exoplanetary objects. As a fleet, these missions remain more powerful than the sum of their parts, oftentimes combining their individual strengths to tackle science together as a team. Each mission will continue to enable impactful science in the upcoming five years that directly address NASA strategic science priorities, and each is returning science to a broad community of users in both new and archival forms. The Senior Review Subcommittee recommends that NASA continue to operate and support each of these missions, and we offer specific recommendations below.

The individual panel reports contain detailed assessments and recommendations regarding each of these missions. This report provides a high-level assessment of the portfolio. Additionally, this report discusses a number of issues that impact multiple missions or the full portfolio. For reference, the missions considered in this review are, in order of launch date:

Name	**Full Name**	**Launch Date**
Hubble	Hubble Space Telescope	1990
Chandra	Chandra X-Ray Observatory	1999
XMM-Newton	X-ray Multi-Mirror Mission - Newton (*ESA mission*)	1999
Swift	Neil Gehrels Swift Observatory	2004
New Horizons	New Horizons	2006

Fermi	Fermi Gamma-ray Space Telescope	2008
NuSTAR	Nuclear Spectroscopic Telescope Array	2012
NICER	Neutron Star Interior Composition Explorer	2017
TESS	Transiting Exoplanet Survey Satellite	2018

Scientific Merits

Individually, and as a jointly operating portfolio, these missions continue to advance the strategic key questions of NASA APD: "Are we alone?", "How did we get here?", "How does the universe work?". A full description of the scientific capabilities and highlights is beyond the scope of this report, but by way of a few examples:

- The Great Observatories–Hubble, Chandra, and XMM-Newton–provide immense multi-wavelength, multi-resolution capabilities to discover and study galaxies from the end of reionization to the present day, trace the evolution of gas as it flows from the intergalactic, through the circumgalactic, and into the interstellar medium, forming stars, heavy elements, and driving black hole evolution.
- TESS is discovering planets and multi-planet systems around nearby stars, pushing the number of known exoplanets beyond 5,000 to date, and is driving new advances in the understanding of exoplanet demographics, while Hubble probes exoplanet atmospheres to understand their diverse compositions.
- NuSTAR and NICER test physics at the extremes of energy and gravitational environment, with NICER providing masses and radii of neutron stars, while NuSTAR probes the regions nearest black holes to study the complex nature of accretion flows.
- Fermi and Swift provide constant watch on the sky for high-energy transient events, discovering and localizing Gamma ray, X-ray, and UV emission from a variety of sources, including multi-messenger sources like gravitational wave and neutrino events.
- New Horizons has made a preliminary measurement of the cosmic optical background, leveraging its unique place in the Solar System to observe UV and optical light with significantly less zodiacal extinction.

Cost Efficiency and Data Availability

The Subcommittee finds that the missions under review are all operating efficiently, providing an excellent scientific return on investment. Most missions have reached an equilibrium, whereby operations costs are at or near the minimum value needed to maintain science productivity. More recent entrants into the extended phase are on the trajectory to that equilibrium. The missions within the APD portfolio are each meeting their extended mission charge well: to enable a broad community of users and to prioritize maximal access to the data through archives and data analysis portals. These include the Mikulski Archive for Space Telescopes (MAST), the High Energy Astrophysics Science Archive Research Center (HEASARC), the Infrared Survey Archive (IRSA), and the Chandra Data Archive (CDA).

For convenience's sake, we refer to community research support as “GO,” a catch-all term for Guest Observer, Guest Investigator, Archival, and Theory programs, throughout the remainder of this document. GO programs remain the focal point for community access, both by funding scientific research and by training the next generation. The Subcommittee continues to stress the critical importance of GO programs to maintaining the robust scientific productivity of the missions and makes its budgetary recommendations in this report with this productivity in mind.

Ranking of Missions

The Senior Review Subcommittee, in accordance with its charge, ranked the nine missions into tiers. The rankings are as follows, in alphabetical order within each tier:

Tier 1	Chandra, Hubble
Tier 2	Swift, TESS
Tier 3	Fermi, NICER, NuSTAR, XMM-Newton
Tier 4	New Horizons

Each of the missions considered are producing high-quality science, and each is in alignment with NASA's strategic science goals. The missions present a broad portfolio of capabilities that impacts nearly every aspect of astronomy today. Furthermore, the missions continue to increase their ability to work together as a fleet, particularly to respond to the transient universe, with their individual capabilities combining to better understand the physical processes behind the dynamic universe.

Hubble and Chandra occupy the top tier given their immense, broad impact on astronomy. These Great Observatories continue to enable a very large number of well-cited publications, with an increasing fraction of publications stemming from archival studies, indicating that their science will endure well after these missions end. The subcommittee notes the immense public impact these missions have as well, helping to inspire the world with their science, and to set new generations of astronomers down the path to future discovery. Hubble, entering its third decade of science, continues to provide unique optical and UV imaging and spectroscopy, with no comparable UV facility planned beyond the next decade. Chandra, even with the loss of the HRC, remains the most powerful X-ray facility in orbit at 1-10 keV. Both missions are operating at extremely high efficiency, and although they are increasingly showing signs of age, both are likely to continue to generate world-class science throughout the next half decade, operating in concert with JWST as it begins its flagship role.

The remaining tiers follow the rankings as described in the Rest of Missions (RoM) panel report. Each of these missions demonstrate great capability and continued potential, and each are recommended to proceed into their next extended mission.

Swift and TESS, by virtue of their impacts and capabilities, occupy the second tier. Swift, nearly two decades after launch, continues to provide exceptional capabilities for time-domain and multi-messenger astrophysics. TESS, after entering its extended mission phase after the 2019 Senior Review, provides high-precision, high-cadence photometry that continues to enable extraordinary discoveries in exoplanet populations, stellar astrophysics, and behavior of Galactic and extragalactic transients. The RoM panel rated Swift highest, emphasizing the team's continued responsiveness to community needs in an evolving scientific environment. In concurrence with the RoM panel, the Subcommittee salutes the TESS team for rapidly building a large and diverse user community that enthusiastically pursues TESS science, while also noting that for future Senior Review cycles it will be important for TESS to follow the path of increasing operational efficiencies for continuing extended missions.

The RoM panel ranks Fermi, NICER, NuSTAR, and XMM-Newton as effectively equal. All four are highly productive missions probing distinctive regimes of wavelength, sensitivity, and timing, and their complementary capabilities make a powerful suite. Each of these missions is well run, and is making innovative efforts to maximize its science return and support its user community. Extended discussion of the individual missions can be found in the RoM report.

As emphasized in the RoM report, New Horizons is unusual in the context of the Astrophysics Senior Review because it is a PSD mission that is requesting APD support for a fraction of its second extended mission, enabling observations that take advantage of its vantage point beyond most zodiacal light and geocoronal Lyman-alpha emission. This proposal offers unique opportunities for astrophysics, but it is much narrower in scope than the proposals from other missions, which is unsurprising because the proposed observations represent a small fraction of the mission's observing time. We emphasize that the Subcommittee ranking refers only to the astrophysics component of the New Horizons extended mission, not to its solar system and heliophysics components, which we were not tasked with evaluating. We concur with the RoM panel that APD should support the effort to obtain and archive the proposed New Horizons observations–as long as it is not at the expense of funding the priorities described below–while funding the scientific analysis of the data through mechanisms that are open to the broader astrophysics community.

Global Budget Issues

As missions move from prime phase to extended mission, they are expected to find cost-saving efficiencies in their operations. This gain of efficiency typically continues through the first couple of Senior Review cycles, after which there are few further gains to be had. A given Senior Review is considering missions at different stages of this lifecycle. It would be valuable to a future Senior Review Subcommittee to have data from NASA showing total budget, number of FTEs, and GO funding for each mission as a function of years since first entering Senior Review.

In this Senior Review cycle as in previous cycles, most missions have in-guide budgets that are flat in real-year dollars (a.k.a. "flat-flat"). In the presence of mild inflation (<= 2%), this practice has worked as a slow pressure on missions to find continuing cost efficiencies. However, it has also slowly eroded the ability of GO funding to support students, postdocs, and faculty.

The sharp recent increase of inflation makes flat-flat budgeting much more problematic. The impact is especially evident for missions where many employees are governed by *mandated* cost-of-living increases. In these cases, flat-flat budgets can impose large fractional reductions in FTE support over the course of 3-5 years. The ability to retain and recruit personnel may be severely impacted even when salary increases are not legally mandated.

We do not have any easy solutions to this problem to propose, but we note that conventional practices on extended mission in-guide budgeting will need to be reconsidered if >2% inflation becomes the norm.

Cross-Mission Issues

The level of communication between mission teams is impressive overall, allowing a good deal of informal sharing of expertise. Nonetheless, there are opportunities to gain some efficiencies and elevate good ideas through cross-mission coordination, particularly in the areas of Diversity, Equity, Inclusion, and Accessibility (DEIA, discussed below), public outreach, software, and operations planning.

With regard to public outreach, Hubble Space Telescope has set the world standard in bringing scientific discoveries to the general public, inspiring new generations of scientists and science-enthusiasts. STScI maintains a large public communication staff (listing 13.8 FTE in the "Communication to the Public" line of their in-guide budget). NASA should explore ways to leverage the expertise and connections of the STScI staff to support public communications for other missions in the astrophysics portfolio.

Diversity, Equity, Inclusion, and Accessibility

Each mission approached how to discuss its DEIA activities differently, as each had access to different types of data (e.g., about the diversity of its user community), and each interpreted what NASA meant by DEIA differently. The Subcommittee recommends that NASA create more concrete and robust DEIA guidance to give the missions the ability to formulate DEIA PMOs well in advance of the next Senior Review. The Subcommittee was encouraged to see that one of the flagship missions had already developed a PMO explicitly tied to inclusion. We would like to see other missions produce PMOs with specific, measurable outcomes that future Senior Reviews can use to gauge the impact of their DEIA activities. Further discussion of specific DEIA initiatives is presented in the panel reports.

In this context, it is important to remind all the missions that the NASA core values are intended to inform all of the agency's, and therefore all of the missions', activities. In this spirit, the missions should be incorporating DEIA across all their PMOs, whether scientific or technical, much as they do safety, for example. The Subcommittee encourages missions to spend more time thinking introspectively about the DEIA work that they already do and to think of this work as a thread that runs through all their activities. One positive example we have seen of this is in emphasizing accessibility in thinking about how software for missions is developed and distributed.

The Subcommittee strongly recommends that all missions regularly conduct climate surveys, designed with expert input. While some tailoring of surveys to individual missions is needed, centralized support for climate surveys would be helpful for smaller missions and can insure a better degree of uniformity and implementation of best practices across the mission suite. We recognize that for small missions these surveys may seem unnecessary, while for the flagship missions this may be complicated by the size and distribution of the relevant stakeholder communities. However, without these regular check-ins, it is impossible to assess how missions are faring in terms of supporting their internal-facing DEIA goals. We caution, though, that such exercises are wasted and indeed counterproductive if there is no follow-through on survey findings and urge the missions and SMD to develop mechanisms for accountability. The results of the surveys should be included in proposals to future Senior Reviews.

Most of the DEIA initiatives proposed by the missions were outward-facing. These bottom-up, mission-initiated approaches to addressing NASA's newest core value of inclusion are important, but they need to be amplified and supported by SMD- and agency-wide efforts to enable their success. The example of the hiring of a DEIA expert at the senior leadership level at STScI, and of another to be shared by the GSFC Guest Observer Facilities, are encouraging, but given the scale of the work that these experts will need to accomplish—addressing DEIA issues both internal and external—these positions will need strong support and resources.

Recommended Implementation Plan

It is the Subcommittee's recommendation that all the APD missions under review enter another extended mission, ideally at or beyond their in-guide funding requests. As explained in detail in the RoM panel report, the Subcommittee also recommends that the New Horizons mission execute the proposed astrophysics experiments, but with the proviso that the data be available for community analysis via ADAP or a similar scheme.

If enhanced support is available to the missions, the Subcommittee ranks the over-guide requests in the below order of priority.

Priority 1	The Rest of Missions over-guide tier 1 recommendation
Priority 2	The majority of the Hubble and Chandra over-guide request
Priority 3	The Rest of Missions over-guide tier 2 recommendations
Priority 4	The remaining Hubble and Chandra over-guide requests
Priority 5	The Rest of Missions over-guide tier 3 recommendations

The subcommittee regards nearly all the over-guide requests from all missions as well motivated ideas that would improve the science return to the community. The subcommittee spent considerable time discussing the prioritization of these over-guides, recognizing that budget limitations will probably not allow NASA to fund all of them. Two challenges in this consideration are the very different scale of the Hubble/Chandra budgets from those of the other missions, and the different choices made by missions in how to prioritize GO funding relative to infrastructure and operations in defining their in-guide budgets. The panel noted the differing methods adopted by the Hubble and Chandra teams in the over-guide requests to advance the common goal of maintaining their high scientific productivity. The specifics of the prioritization above is as follows, predicated on the assumption that NASA will fund the DEIA position shared by the GSFC Guest Observer Facilities described in the proposals submitted to the RoM panel. As noted by that panel, some missions included that budget ($50K/year) in their in-guide budget and others in their over-guide budget. In agreement with the RoM panel, we recommend that this program not be charged to mission budgets, and we prioritize this support above any of the other over-guide requests.

The RoM panel report prioritizes over-guide requests in three tiers, repeated here for convenient reference (items within a tier are not priority ranked):

Tier 1:

The XMM-Newton mission request for a programmer to meet new SOC requirements and to retire a significant succession planning risk.

Tier 2:

a. The joint Swift/NICER over-guide requests to fund a postdoctoral scientist to improve efficiency and remove redundancy in scheduling coordinated observations.

b. The Swift initiative to improve the photometric precision of Swift UVOT data.

c. The full suite of NuSTAR over-guide requests.

Tier 3:

a. Augmentation of GO funding support across the missions, beginning with augmentation of GO funding of TESS, followed by the XMM-Newton request to augment GO support to allow for C-ranked proposals to receive more funding.

b. The Swift initiative to document and publicly release the BAT software.

The Subcommittee offers the following advice for interleaving these recommendations with that of the Hubble and Chandra over-guide requests. Recognizing the uncertainty in future budgets, this advice is deliberately inexact. Further details may be found in the individual panel reports.

1. The first priority should be the RoM tier 1. This request is inexpensive compared to others, and it is important for maintaining the U.S. community's stake in one of the world's most powerful X-ray observatories.

2. The next priority should be to fund substantial fractions of the Hubble and Chandra over-guide requests. These missions are highly optimized and have been so for a significant time. Failing to provide over-guide funding to Hubble and Chandra would severely impact their science output. With regards to Chandra, the subcommittee suggests prioritizing at this level support for i) the preservation of the current staffing levels, and ii) the addition of two engineers in the operations team. However, if full funding of this "basic" over-guide is not achievable, the committee recommends that the Chandra team should consider reducing the GO funding if needed to maintain observatory operations at an acceptable level. If full funding of the Hubble over-guide is not achievable, the Hubble team should consider seeking further efficiencies in its operational and community outreach support in order to preserve as much as possible the level of GO funding. The guiding principle for both missions is that over-guide requests should be allocated to maximize the science returns for the community, which is sometimes best achieved by preserving mission infrastructure while maximizing GO funding.

3. The next priority should be the RoM tier 2 items. If substantial fractions of the Hubble and Chandra over-guides can be supported, the subcommittee recommends supporting this tier of RoM overguides even at the cost of not fully funding the Hubble and Chandra overguides.

4. The next priority should be additionally funding the Hubble and Chandra over-guide requests The Hubble over-guide is fully directed to maintaining the level of GO funding. With regard to Chandra, the subcommittee suggests prioritizing at this level support for an additional software engineer in the CXC Data Systems group to develop and maintain tools that will enhance Chandra's ability to further support time-domain science. If additional support is available, Chandra's requested over-guide for increase of support of GO programs is recommended. The Subcommittee did not endorse the Chandra DEIA over-guide request.

5. The Subcommittee considers the RoM tier 3 items worthwhile, and that each would substantially increase the science output of the associated mission, should budget flexibility be sufficient to support them.

Planning for the Future

The Subcommittee notes that many of these missions are now multiple decades old, and that they are increasingly prone to service interruption or component failure. While none of the missions identified an expectation of significant failures over the next few years, it is nonetheless important to begin contingency planning for many of these missions. Here, by "contingency planning" the Subcommittee does not mean a series of if/then decision rules at an individual capability layer. Instead, and especially in the case of Great Observatory class missions, contingency planning refers to a set of scientific optimization strategies that would take the missions out of their current modes of operation. The Subcommittee felt strongly that this planning be performed with significant community engagement to take incorporate the broadest possible creativity.

As an example, Hubble should give consider whether to continue to allocate GO time spanning single orbit through treasury scale (and the associated support resources that are needed to support all these scales of observation) in the manner in which it has made most of its time allocation over the last three decades, or whether to prioritize larger campaigns to utilize and best harvest unique capabilities before they are lost. The missions at every scale considered by this review are not beholden to their operations and GO time allocations models through to their end. Instead, with an eye towards maximizing science from a diminishing capability over time, missions should begin to engage their full communities to explore how they might operate differently.

Equally important for the missions to consider while they are still operating is how to maximize the longevity, usefulness, and science impact of their data archives. Missions must continue to strive to maintain the provenance knowledge of all the data in the archives, and should allocate resources with closeout in mind now, instead of waiting for an instrument or spacecraft failure. This is especially true for those missions where the deep knowledge of the data resides in those staff nearing retirement. Moreover, given the increased importance missions are placing on coordinated observations, resources should be allocated towards increasing cross-mission data discovery within archives.

Acronym List

ADAP	Astrophysics Data Analysis Program
APD	Astrophysics Division
BAT	Burst Alert Telescope
CDA	Chandra Data Archive
CXC	Chandra X-ray Center
DEIA	Diversity, Equity, Inclusion and Accessibility
ESA	European Space Agency
FTE	Full-Time Equivalent
GO	Guest or General Observer
GSFC	Goddard Space Flight Center
HEASARC	High Energy Astrophysics Science Archive Research Center
HRC	High Resolution Camera
IRSA	Infrared Survey Archive
JWST	James Webb Space Telescope
MAST	Mikulski Archive for Space Telescopes
NASA	National Aeronautics and Space Administration
NICER	Neutron Star Interior Composition Explorer
NuSTAR	Nuclear Spectroscopic Telescope Array
PMO	Primary Mission Objective
PSD	Planetary Science Division
SLAC	Stanford Linear Accelerator Center
SMD	Science Mission Directorate
SOC	Science Operations Center
STScI	Space Telescope Science Institute
TESS	Transiting Exoplanets Survey Satellite
UV	Ultraviolet
UVOT	Ultraviolet Optical Telescope
XMM	X-ray Multi-Mirror Mission