# 2019 Astrophysics Senior Review

## Senior Review Subcommittee Report

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**June 4-5, 2019**

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## EXECUTIVE SUMMARY

The eight missions evaluated by the 2019 Astrophysics Senior Review constitute a portfolio of extraordinary scientific power, on topics that range from the atmospheres of planets around nearby stars to the nature of the dark energy that drives the accelerating expansion of the cosmos. The missions themselves range from the venerable Great Observatories *Hubble* and *Chandra* to the newest Explorer missions *NICER* and *TESS.* All of these missions are operating at a high level technically and scientifically, and all have sought ways to make their operations cost-efficient and their data valuable to a broad community. The complementary nature of these missions makes the overall capability of the portfolio more than the sum of its parts, and many of the most exciting developments in contemporary astrophysics draw on observations from several of these observatories simultaneously. The Senior Review Subcommittee recommends that NASA continue to operate and support all eight of these missions. We include specific budget recommendations below.

The individual panel reports (Chandra, Hubble, and Rest-of-Missions) contain detailed assessments and recommendations regarding each of these missions. This report provides a high level assessment of the portfolio and addresses a few cross-cutting issues. For reference, the missions considered in the 2019 Senior Review are, in order of launch date:

- Hubble Space Telescope (*Hubble*)
- Chandra X-ray Observatory (*Chandra*)
- X-ray Multi-Mirror Mission-Newton (*XMM-Newton*)
- Neil Gehrels Swift Observatory (*Swift*)
- Fermi Gamma-ray Space Telescope (*Fermi*)
- Nuclear Spectroscopic Telescope Array (*NuSTAR*)
- Neutron Star Interior Composition Explorer (*NICER*)
- Transiting Exoplanet Survey Satellite (*TESS*)

## SCIENTIFIC MERITS

The strategic objectives of the NASA Astrophysics Division address questions as old as human thought: *How does the universe work? How did we get here? Are we alone?* Today's astrophysics missions are providing a constant stream of remarkable discoveries that offer new insights on these enduring questions. To give just a few examples:

- *TESS* is discovering transiting planets around nearby bright stars, yielding new understanding of planetary composition and demographics and identifying planets whose atmospheres can be probed with observations from *Hubble* and, in the future, the *James Webb Space Telescope* (*JWST).*
- *Hubble, Chandra,* and *XMM-Newton* are tracing the evolution of supermassive black holes, galaxies, and galaxy clusters from redshifts $z > 6$ to the present day, revealing the complex interplay between large scale gas accretion, star formation, central black hole growth, and feedback that expels gas and heavy elements back to the intergalactic medium.
- *NuSTAR* is revealing the innermost regions of accretion flows onto black holes and measuring their spins, and *NICER* is measuring the masses and radii of isolated neutron stars to constrain their equation of state; both missions probe extreme physics that tests our fundamental understanding of gravity and matter.
- *Swift* and *Fermi* provide continuous monitoring of the transient high-energy sky, discovering the electromagnetic counterparts to ultra-high-energy neutrino and gravitational wave events, which can be spectroscopically monitored by other missions as they fade.
- *Hubble, TESS, Chandra,* and *NuSTAR* are transforming our understanding of the stellar life cycle with UV and near-IR observations of star-forming regions, asteroseismic constraints on the internal structure of main sequence and evolved stars, and detailed element-by-element X-ray maps of supernova remnants.

Studies of astrophysical transients and time-domain phenomena are perhaps the most rapidly growing field of astrophysics, rich with opportunities for exciting discoveries. The mission portfolio is well positioned to exploit these opportunities, which require effective coordination between ground and space observations. Developing optimized multi-mission strategies for localization of gravitational wave or neutrino events and for target-of-opportunity observations of these sources and of the flood of events from electromagnetic transient surveys is an important challenge for the next half-decade.

## COST EFFICIENCY AND DATA AVAILABILITY

Extended mission phases are generally an excellent scientific investment because they leverage the large investments already made in mission design, construction, and launch. Operations costs usually decline as missions identify efficiencies during their extended phase, so a large fraction of the funding in an extended phase goes directly into increasing the mission's scientific yield. Senior Review is an effective procedure for ensuring that a mission does not continue if its capabilities have been surpassed or have declined to the point that they no longer enable ground-breaking investigations, or if the questions that can be addressed by the mission are no longer at the scientific frontier. None of the missions considered in this Senior Review fall in this category.

Well funded Guest Observer/Guest Investigator (GO/GI) programs have a double payoff, since they produce scientific results and in the process train young investigators who become the scientific leaders of future projects and who support the nation's basic needs in science and technology. The Chandra, Hubble, and Rest-of-Missions panel reports emphasize the value of robust GO/GI programs tied to these missions, in addition to the cross-mission research support available through other NASA grant programs.

As detailed in the panel reports, we judge that all of the missions in this Senior Review are operating in an efficient manner that provides excellent value to NASA and the nation. All of them are attentive to building a broad user base and providing data access that supports those users' science investigations; several of the missions are exemplary on this score, as detailed in the panel reports.

While every mission comes to an end, its data do not, and scientific concerns about data and usability extend beyond mission lifetimes. Effective use of scientific archives must consider both access (including access to discovery) and usability (documentation, citations, analysis and interpretation software, including guides and documentation). The current missions provide archives such as the Chandra Data Archive (CDA) that support their users with both data access and analysis tools, and the Mikulski Archive for Space Telescopes (MAST), High Energy Astrophysics Science Archive Research Center (HEASARC), and Infrared Survey Archive (IRSA) provide powerful cross-mission archives that facilitate multi-wavelength investigations. Future Senior Reviews could benefit from more direct coordination with the NASA archive reviews to help ensure that the long term impact of missions extends beyond their operational lifetimes.

## RANKING OF MISSIONS

In accord with its charge, the Senior Review Subcommittee ranked the eight missions into tiers.

| Level | Missions |
|---|---|
| Tier 1 | Hubble, Chandra |
| Tier 2 | TESS, Swift |
| Tier 3 | Fermi |
| Tier 4 | NICER, NuSTAR, XMM-Newton |

We emphasize that the missions in all four of these tiers are producing high quality science at an impressive rate, and that each of these missions is led by a strong and committed team. The Chandra, Hubble, and Rest-of-Missions Panels rated every one of these missions as either "Excellent" or "Excellent/Very Good" in overall score. An effective astrophysics portfolio requires both broadly capable missions like *Hubble* and *Chandra* and more focused missions that push technical boundaries in a way that enables breakthrough science in particular domains.

*Hubble* and *Chandra* occupy the topmost tier because of their extraordinarily broad scientific impact. Nearly three decades after launch, and rejuvenated multiple times by servicing missions, *Hubble* remains the most famous telescope in the world, an icon of American scientific achievement. Its exquisite image quality and its UV imaging and spectroscopic sensitivity are unique; the UV sensitivity will not be equalled for at least the next 15 years. The 900+ peer-reviewed papers a year arising from *Hubble* data span the full range of astronomy and astrophysics, from Europa's water plumes to the primeval galaxies of cosmic dawn. Nearly two decades after launch, *Chandra* remains the world's most powerful X-ray telescope at 1-10 keV energies thanks to its unique arcsecond resolution combined with high effective area and diffraction-grating spectroscopic capability. The 400+ peer-reviewed papers a year arising from *Chandra* reveal the full richness of high-energy astrophysical phenomena, including the tidal disruption of stars by black holes, the X-ray flares that may lash the atmospheres of young planets around low mass stars, and the echoes of quasar outbursts that pulse through the hot gas of massive galaxy clusters. Both of these Great Observatories are operating at high efficiency, provide outstanding service to a worldwide community of users, and regularly produce results that resonate with the public across the U.S. and around the globe.

For the remaining missions, the Senior Review Subcommittee adopts the same tiers defined by the Rest-of-Missions Panel and justified in their report. While these missions do not individually have as broad an impact as *Hubble* and *Chandra*, each of them has unique capabilities and collectively they enable ground-breaking discoveries in every domain of contemporary astronomy.

*TESS* and *Swift* occupy the topmost of these tiers; *TESS* because of its revolutionary impact on the fields of exoplanets and stellar astrophysics, and *Swift* because of its exceptional abilities in time-domain and multi-messenger astrophysics. Both missions provide models of how to build and serve a broad user base to maximize science return.

*Fermi* comprises the next tier because of its full-sky coverage and its unique access to the gamma-ray spectral range, both of which are enormous assets for multi-messenger time-domain astrophysics.

*NICER, NuSTAR, and XMM-Newton* comprise the final tier. *NICER* has the largest effective area of any telescope at soft X-ray energies, millisecond-level timing precision, and rapid response capability enabled by its location on the International Space Station. *NuSTAR* is the first focusing mission at hard X-ray energies allowing unique investigations of the physics of black hole accretion and numerous other phenomena. *XMM-Newton* is a broadly capable X-ray observatory, with high sensitivity across the 0.2-12 keV spectral range, wide field of view, spectroscopy at both CCD and diffraction-grating energy resolution, and imaging resolution second only to *Chandra*. Because *XMM-Newton* operations are supported by the European Space Agency (ESA), NASA's investment in funding U.S. investigators has an exceptionally high return.

## IMPLEMENTATION PLAN

NASA should strive to support all eight of the missions considered by the 2019 Senior Review at or above the level of their baseline requests. In the case of *Hubble* and *Chandra*, "baseline" refers to the in-guide budget submitted in the proposal. For other missions, the Rest-of-Missions Panel defines "baseline" in Section 1 of their report; it is synonymous with "in-guide" except for *NICER* and *Fermi*.

In the event that enhanced support is possible, we recommend following the enhancement recommendations in Section 8 of the Rest-of-Missions panel report, with the prioritization enumerated there. Although *Hubble* and *Chandra* comprise our first tier of missions, they already have the highest budgets, and small enhancements could have their biggest scientific impact through the other missions. We note that the total cost of all of these proposed enhancements for FY21 (taken as a representative year) is $2.5M, a small fraction of the approximately $200M summed FY21 budgets for the missions reviewed here.

In the event that cuts below the baseline level are necessary, we recommend a balanced distribution across the portfolio rather than cancelling the operations or GO/GI support of an individual mission. *Hubble's* budget is the one most capable of absorbing short term fluctuations because of its overall size and because of the overlap of personnel between *Hubble*, *JWST*, *WFIRST,* and MAST. For other missions, Section 8 of the Rest-of-Missions panel report provides guidance on budget cuts should they prove necessary.

*Chandra* did not submit an over-guide budget request, but we note that absorbing the impact of inflation within its constant projected budget is likely to eventually compromise the mission's ability to maintain operational effectiveness. We advise NASA to be attentive to this risk and make adjustments if possible.

The landscape of time-domain astronomy is changing at an extraordinary pace. The potential for new discoveries connected to gravitational wave events is especially exciting, and it presents many complexities associated with localization and optimal use of follow-up resources. The Rest-of-Missions panel report recommends that NASA convene a meeting of mission leaders "to foster development of a coordinated strategy, communication, and shared tools for electromagnetic observations of gravitational wave events or other rare transients of high scientific importance." The Senior Review Subcommittee recommends that *Hubble* and *Chandra* be included in such a forum.

## OVERALL ASSESSMENT

NASA's suite of operating missions is well constituted to address the priorities of the SMD Science Plan and the 2010 Astrophysics Decadal Survey. They present an appropriate balance between the broadly capable Great Observatories and the smaller scale missions that have unique capabilities in particular domains. The missions reviewed here cover wavelengths from the near-IR through optical/UV to X-rays and gamma rays. They are complemented by the mid-IR and far-IR capabilities of *SOFIA* and, in the reasonably near future, they will be further complemented by *JWST* and *SPHEREx*.

The collective impact of these missions and their unified data archives makes a whole that is greater than the sum of its parts. The rapidly changing landscape of time-domain astronomy presents exciting opportunities and new challenges. Mission teams and NASA Astrophysics Division leadership should explore ways to maximize the effectiveness of the full mission portfolio in addressing these opportunities and challenges.

Reviewing this suite of missions has been a refreshing experience. Missions that began their scientific lives a decade or more ago have re-invented themselves in ways that respond to changing science opportunities and the goals of the worldwide astrophysics community. They are joined by new missions that provide transformative capabilities in new domains and that are rapidly building user communities of their own. The scientific achievements of these missions are a tribute to the mission teams and to the skills and creativity of the scientists who build on what they have provided.

# 2019 Astrophysics Senior Review

## Chandra Report

# 2019 Astrophysics Senior Review - Chandra Report

**May 13-15, 2019**

**PANEL**

Co-Chair: Wilton Sanders (NASA/University of Wisconsin retired)
Co-Chair: Maura Fujieh (NASA/Ames)
Joel Bregman (University of Michigan)
Daryl Haggard (McGill University)
Patrick Hartigan (Rice University)
Sebastian Heinz (University of Wisconsin, Madison)
Philip Kaaret (University of Iowa)
Samar Safi-Harb (University of Manitoba)

## EXECUTIVE SUMMARY

The *Chandra X-ray Observatory* continues its outstanding performance as a NASA Great Observatory, offering impressive science impact twenty years after launch. Scientists use *Chandra*'s unparalleled sub-arcsecond resolution and sensitivity to achieve novel, ground-breaking science not attainable with any other X-ray facility. This exceptional angular resolution is essential for interpreting crowded fields and extended emission. *Chandra* is highly synergistic with other current and future observatories across the electromagnetic spectrum, including the James Webb Space Telescope (JWST) and the Large Synoptic Survey Telescope (LSST). *Chandra's* merits are particularly noteworthy in the emerging arena of multi-messenger astrophysics. Its capabilities enable critical studies of compact objects, accretion shocks, extragalactic clusters, supernova remnants, pulsar wind nebulae, stellar chromospheres, and the response of exoplanet atmospheres to stellar flares.

*Chandra* is a unique national asset stewarded by an exceptional team who protect the health of the observatory while pushing to accomplish high-impact and often unanticipated, new science. The *Chandra* team is highly responsive to the scientific community, providing excellent support over the entire data acquisition sequence from proposal preparation to data distribution, analysis and archiving. The team prides itself on rapid data collection and distribution (< 2 days between the observation and delivery of data). The *Chandra* Data Archive sees annual average downloads of 18 TB to sites in 108 countries. The recent release of the *Chandra* Source Catalog 2.0 further increases the observatory's long-term archival impact. From its inception, the *Chandra* team has fully embraced a commitment to having community input drive science target selection and the overall science program. This approach allows *Chandra* to stay at the scientific cutting edge and maintain the highest level of relevance across fields.

The *Chandra* team continues to identify creative ways to optimize use of available funds, including regular appraisals and improvements to operational processes and procedures. Where possible, automation is being used across the project to respond to increased resource demands, particularly in the area of mission planning.

*Chandra* has been on orbit for almost 20 years and while there has been some degradation, most subsystems continue to perform well. The degradation of the spacecraft's multi-layer insulation and other thermal protective surfaces is the primary spacecraft issue and increases operational complexity, while the continued buildup of contamination on the ACIS optical blocking filter, reducing its sensitivity in the soft X-ray band, is the main issue affecting *Chandra* instruments.

*Chandra's* oversubscription rate remains high, 5.5 in observing time, and the worldwide community of *Chandra* users exceeds 4300. *Chandra* scientists have published more than 7700 refereed papers, with approximately 450 added each year. *Chandra* offers a training ground for early career scientists, and its impact reaches into the public sphere engaging the next generation of scientists, including high school students.

*Chandra* excels in its relevance and responsiveness to the agency's mission. As there is no other astronomical X-ray facility, existing or in development, with comparable angular resolution and sensitivity, *Chandra's* high efficiency, both in operations and cost, offers an excellent return on NASA's investment over the requested three-to-five year funding period.

ADJECTIVAL RATING FOR SCIENCE MERIT: **EXCELLENT**
ADJECTIVAL RATING FOR RELEVANCE AND RESPONSIVENESS: **EXCELLENT**
ADJECTIVAL RATING FOR TECHNICAL CAPABILITY AND COST REASONABLENESS: **EXCELLENT/VERY GOOD**

OVERALL ADJECTIVAL RATING: **EXCELLENT**

**CRITERION A: SCIENTIFIC MERIT**

The *Chandra X-ray Observatory* supports an exemplary science program, a remarkable achievement for a facility celebrating its 20th year in space. One reason for *Chandra*'s strength is its unique high angular resolution, which enables scientific studies not possible with any other facility. *Chandra* continues to lead remarkable new discoveries, such as the first detection of an X-ray counterpart to the gravitational waves emitted when two neutron stars collided in a galaxy only 40 Megaparsecs from our own. *Chandra* has also been witness to a variety of rare and remarkable phenomena, such as tidal disruption events (a star being torn apart by a black hole), the response of exoplanet atmospheres to stellar flares, and powerful outbursts from ultraluminous X-ray sources (ULXs). More broadly, *Chandra* supports key research in diverse areas including (but not limited to) compact objects, accretion shocks, supernova remnants, pulsar wind nebulae, stellar chromospheres, and extragalactic clusters. The science highlights below utilize new and archival *Chandra* data, emphasizing the importance of both aspects of the observatory's excellence areas.

***Neutron Star and Black Hole Mergers***: The *Chandra X-ray Observatory* has helped drive recent multi-messenger discoveries using capabilities unlike any other mission in NASA's fleet. Its combination of sub-arcsecond resolution and high sensitivity enabled the spectacular detection of X-ray emission from the first binary neutron star merger, GW170817, discovered via gravitational waves. These X-ray observations highlight *Chandra's* exceptional ability to combine rapid response "target of opportunity"' and joint facilities observations to enable groundbreaking science, by combining X-rays with observations from the Very Large Array and the Hubble Space Telescope. The early X-ray (non-)detections revealed the first off-axis short gamma-ray burst and connected it to neutron star mergers, kilonovae, and GRB afterglows, placing the observations into a powerful observational and theoretical framework for understanding the merger and its outflows. *Chandra* is the *only* X-ray observatory that cleanly distinguished GW170817 from other nearby X-ray sources, including the host galaxy's active nucleus, and the *only* observatory that continues to watch its X-ray flux decay over long time scales (now approaching two years).

Despite the incredible success of *Chandra* and other NASA observatories' monitoring of GW170817, mysteries remain. Models indicate that the compact remnant could be a heavy neutron star or a light black hole. Approved *Chandra* Director's Discretionary Time and General Observing (GO) allocations ensure monitoring of GW170817 until 2020, helping to constrain models for the remnant and the ejecta. *Chandra* will also play a key role in the discovery and monitoring of electromagnetic counterparts to new LIGO-Virgo (and KAGRA) gravitational wave sources, likely including the first black hole-neutron star merger. It already supports multiple approved programs to monitor and characterize the X-ray and radio counterparts of about a half dozen binary neutron star or neutron star and black hole mergers over the next several years.

Meanwhile, connections between fast X-transients and neutron star mergers are also shedding light on this rapidly-evolving field. Several new sources have been identified in the *Chandra*

Deep Field South and observations support their interpretation as rapidly-spinning neutron stars boasting strong magnetic fields, *i.e.*, magnetars. Without a firm redshift determination, the first detection, CDF-S XT1, left interpretations open allowing an off-axis/low-luminosity short gamma-ray burst, or the tidal disruption of a white dwarf by an intermediate-mass black hole. The second source CDF-S XT2 at z = 0.738 is fully consistent with an X-ray transient powered by a millisecond magnetar. Future *Chandra* studies will be crucial to confirm this finding.

***Tidal Disruption Events***: Transient X-ray phenomena like those described above are also key to understanding variability in supermassive black holes (SMBHs). Supermassive black holes typically grow by accretion of interstellar gas, but dynamical interactions can also increase their mass, *e.g.*, capture or "spaghettification" of an unlucky star that ventures too close to the black hole. These so-called tidal disruption event (TDE) flares, and the subsequent accretion of the star's mass onto the SMBH, offers a window into the physics driving black hole (BH) variability. Joining forces with *XMM-Newton*, *Chandra* scientists have monitored the circularization of ~ 2 solar masses of material accreting onto a ~ $10^6$ $M_\odot$ BH and used the emission to study the optically thick, low-temperature corona, similar to those observed in accreting stellar-mass BHs. These teams have also recently discovered a 131-second quasi-periodicity from the spectacular transient, ASASSN-14li, which is likely to be a tidal disruption event. The X-ray analysis indicates that this periodicity originates from very close to the SMBH's event horizon, and that the black hole is spinning rapidly. High sensitivity *Chandra* observations of other TDEs are thus poised to uncover quasi-periodicities that encode information about the fundamental properties of the SMBHs, allowing major advances in this field in the coming several years.

***Imaging Supermassive Black Holes***: *Chandra* has joined forces with another exceptional new astrophysics experiment, the *Event Horizon Telescope* (EHT), to model and interpret the *first* direct images of supermassive black holes (SMBH). The world was swept off its feet by the EHT images of the silhouette of M87's black hole and *Chandra* data from coordinated campaigns helped rule out models that over-predicted the X-ray flux, offering improved constraints on the black hole spin, mass, and other fundamental properties. These joint *Chandra* and EHT observations also provided direct evidence that accretion onto the M87 SMBH can fuel jets. *Chandra* is the only X-ray observatory capable of directly resolving the Bondi accretion radius of nearby supermassive black holes, coupling the accretion of hot gas to the inner X-ray jets. This domain is poised to become one of the most powerful joint capabilities of *Chandra* with the EHT.

These unique synergies between *Chandra* and the EHT will be even more important for the Milky Way's SMBH, Sagittarius A*. *Chandra* has a long legacy of observing Sgr A*, which is a highly variable X-ray source. Sgr A* was the target of an ambitious *Chandra* X-ray Visionary Program in 2012, which now provides a baseline for understanding the SMBH's X-ray flares and other potential long-term variability. This legacy will be crucial for interpreting the EHT observations of Sgr A*, since the target is variabile on short (hour-long) timescales, compared to the longer (~ days-long) variability of M87. The EHT team is working in close collaboration with *Chandra* and other multi-wavelength observatories to interpret the Sgr A* data and tease out the image, or even the very first movie, describing our closest supermassive black hole.

***Origin and Evolution of Galaxies and Supermassive Black Holes***: *Chandra* is uniquely positioned to study the growth of supermassive black holes and their host galaxies near the end of the cosmic dark ages (z ~ 6-7) since these studies require both excellent X-ray sensitivity and exquisite spatial resolution. Despite years of inquiry, we still struggle to understand how SMBHs build their enormous masses so quickly, appearing with ~$10^8$–$10^9$ $M_\odot$ less than 1 Gyr after the Universe's inception. Scientists using *Chandra* have compiled large samples of luminous quasars at high and low redshift and found no evidence for evolution of the X-ray spectra back to z ~ 6, *i.e.*, accretion flows onto these massive black holes appear to be the same across cosmic time. Future X-ray and radio surveys will target a census of SMBH activity down to the lowest luminosity levels in galaxies of all morphological and spectral types and will probe the link between accretion power (X-rays), jet power (radio), and SMBH mass. The next 3-5 years will see a doubling of the number of z > 6 quasars imaged by *Chandra*, providing a better understanding of the X-ray-to-optical spectra, bolometric luminosities, and Eddington ratios at this early epoch.

*Chandra* has also advanced studies of the smaller siblings to these large black holes, low luminosity and intermediate mass black holes, which may be the "seeds" for the more massive systems. These are often located in dwarf galaxies and are key to understanding how SMBHs formed and grew in the very early Universe. *Chandra* has enabled studies of the existence, masses, and growth rates of many as 50 intermediate mass black hole candidates with masses of a few $10^4$–$10^5$ $M_\odot$ in dwarf galaxies, the most distant at z = 2.39. These discoveries support the stellar-mass seed scenario for massive BH formation and future *Chandra* studies will allow improved differentiation between theoretical models.

***Supermassive Black Hole Feedback***: The launch of *Chandra* catalyzed a fundamentally new view of the formation of cosmic structure, including the co-evolution of supermassive black holes and their host galaxies. Thanks to *Chandra*, we now understand that energetic feedback from black holes plays a critical role in galaxy evolution. *Chandra* continues to be *foundational* to the study of feedback on galaxy-, group-, and cluster scales. It has provided the first bona-fide evidence that feedback by radio jets operates in all of these systems and that the energetics of this "radio mode" feedback are sufficient to provide the required heating. *Chandra* has also been fundamental in studying "quasar mode" feedback through its surveys of X-ray AGN populations and detailed spectroscopy of AGN winds. The recent exciting discovery of quasar-mode feedback in the "Teacup Quasar" SDSS J1430+1339 exemplifies the power of *Chandra's* exquisite spatial resolution in X-rays and gives a tantalizing view of science to come.

The discovery of dozens of X-ray cavities in clusters and groups has become one of *Chandra's* great legacies. Focused and strategic ultra-deep observations of feedback in, for example, Perseus, Hydra, Virgo, and Cygnus A are now providing detailed views of the turbulence and dynamics in clusters that drive new generations of models of cluster formation and evolution. For example, matching VLA observations of Cygnus A with the 2 Msec deep X-ray image of the host cluster provides a direct, arcsecond-resolution map of where and how radio galaxies interact with the intracluster gas. The ongoing campaign to map the structure of the M87 jet demonstrates that no other X-ray observatory can provide the resolution to study jet dynamics and particle transport. The need for very deep and high-resolution observations of feedback underscores the important role *Chandra* will play over the coming decade in understanding the detailed physics of cosmic structure.

***Large Scale Structure and Galaxy Clusters***: Clusters of galaxies are the largest gravitational systems in the Universe, with sizes 100 times that of our Milky Way galaxy and masses 1000 times greater. Understanding how these giants work is a central goal of astrophysics, with *Chandra* scientists leading the field. The hot gaseous component of clusters is made mostly of normal baryonic matter, but dark matter dominates their gravity. Deep X-ray observations have revealed new features in the hot gas that can last for billions of years, “cold fronts” that likely mark a past merger of two clusters. These cold fronts are more common than previously thought and, though they were originally discovered near cluster centers, *Chandra*‘s resolving power now locates them throughout clusters’ full reach. These new discoveries give vital insights into the physics of the gas (*e.g.*, conduction and mixing are weak) as well as the merger rate in clusters.

Cluster evolution can be elucidated by observing these systems over cosmic time, but most studies have been confined to low redshift. Improved methods for identifying higher redshift clusters have been developed in collaboration with the *South Pole Telescope* (SPT), which measures Compton scattering of the cosmic microwave background by the hot cluster gas (the Sunyaev-Zeldovich or S-Z effect). S-Z measurements identify clusters and measure the product of the gas mass and temperature, while X-ray observations measure the temperature, luminosity, composition, and spatial structure of the gas. Together, the X-ray and S-Z measurements give a more complete picture of clusters. Recently, a survey of 147 clusters traced the evolution over most of the age of the Universe (~ the past 10 Gyr). Investigators find that the inner parts (cluster cores) are “frozen” in time, with little evolution, while the outer parts grow, evolve, and eventually relax. Through a complementary technique, the most distant galaxy cluster was discovered in X-ray imaging, demonstrating that we can push back to even earlier times in the Universe. Upcoming *Chandra* cluster surveys based on SPT-Pol observations, which will be more sensitive than SPT to low mass clusters, will test the impact of dark energy and neutrino mass on the growth of structure at these higher redshifts, revealing cluster evolution at earlier times in the Universe.

Ongoing and future galaxy cluster investigations will continue resolving mysteries of cluster physics and evolution. *Chandra* observations of the most extreme clusters are planned, and such deep observations have proven to be particularly revealing. One such cluster, Phoenix, the most X-ray luminous and also the fastest cooling, exhibits a firestorm of star formation in the core region. These core regions are rich in physical processes and reveal a variety of physics, including large scale outflows, cooling instabilities, AGN heating and accretion on small scales. *Chandra* caught another extreme cluster (Abell 2146) in the act of a major merger, creating shock fronts that heat the gas and produce radio-emitting high energy electrons. Another “extreme” cluster is H1821+643, a relatively nearby cluster with a very luminous, broad-line quasar in the center. The quasar is suspected to cause strong Compton cooling, and upcoming *Chandra* observations will measure the gas properties, identify ionized outflows and determine whether hot gas inflows are sustained by this quasar outburst.

***Stellar Evolution and Supernova Remnants***: *Chandra* studies of supernovae (SN) and their remnants (SNR) have opened a new window into the chemical evolution of galaxies, the origin of high-energy cosmic rays and the fate of stars after they die. Studies of their collapsed compact objects (neutron stars and black holes) probe the physics of the most extreme environments, unattainable from laboratories on Earth. *Chandra* has revolutionized this field. For example, X-ray observations of neutron star cooling allow studies of the physical properties of the ultra-dense matter inside these exotic compact stellar remnants. *Chandra* probed what may be the slowest known magnetar ever detected. *Chandra* led to the discovery of torii, jets, and wisps in pulsar wind nebulae (PWNe) stimulating numerical simulations on supercomputers. *Chandra* continues to trace neutron stars velocities and the distribution of the heavy elements ejected following the SN explosion, thus reshaping our understanding of SN explosion mechanism and progenitors.

Recent breakthroughs with *Chandra* include catching the evolution an ordinary hydrogen-poor SN into a strongly interacting, hydrogen-rich SN — a result that challenges current theories of massive star evolution. Meanwhile, continued sub-arcsecond monitoring of SN1987A provides a unique legacy dataset of the closest and youngest extragalactic supernova illuminating our understanding of SN evolution. Frequent monitoring of this source (in concert with studies at other wavelengths) shows that the remnant has recently entered a critical phase of its evolution. In the next 5 years the brightening of the reverse-shocked ejecta will place constraints on the properties of the SN and its progenitor. *Chandra* has also been observing the youngest (~ 100 yr-old) known SNR in our Galaxy G1.9+0.3. Future, planned deep observations of this remnant will monitor small-scale changes to probe its evolution and explosion mechanism. Upcoming deep observations of SNR N132D in the Large Magellanic Cloud will provide an unprecedented look at the spatial distribution of heavy elements and, combined with multi-wavelength data, will address unanswered questions about massive star evolution in a lower metallicity environment.

PWNe are among the most powerful accelerators in the Universe. *Chandra* observations have led to the discovery of a zoo of PWNe and compact objects whose emission mechanisms are not yet understood. Recent DDT observations of a highly magnetized neutron star (J1119-6127), thought to be a rotation-powered radio pulsar, led to the discovery of variability from its compact PWN following a magnetar-like outburst, enabling the first imaging of compact magnetar wind nebulae. Recent images of bow-shock PWNe such as Geminga and the Lighthouse Nebula are simultaneously revealing new high-resolution, elongated structures opening a new window to study many interesting phenomena relevant to other areas in astrophysics, such as MHD turbulence, particle escape and ISM entrainment.

***X-ray Binaries and the Disk-Jet Connection***: The death of a star within a binary stellar system can lead to the formation of an X-ray binary in which a compact object (neutron star or black hole) is fed by accretion of gas from the companion star. *Chandra*'s high angular resolution has been essential in enhancing our understanding of X-ray binaries within our Milky Way Galaxy and nearby galaxies. Correlations between radio and X-ray emission in the decaying phases of outbursts from Galactic black hole X-ray binaries have demonstrated a robust coupling between the accretion flow onto the black hole with the relativistic jets produced in the system. Recent *Chandra* observations of V404 Cygni suggest that fluctuations in the radio lag the X-ray by about 15 minutes. If confirmed with future joint *Chandra*/radio observations, this would indicate that the jet has a size of less than 3 astronomical units providing a crucial constraint on jet models.

An important question that may bear on the origin of binary neutron star gravitational wave events is whether globular clusters, isolated islands with thousands to millions of old stars, contain black holes. Capitalizing on its sub-arcsecond resolution, *Chandra* resolved this question by revealing clear X-ray signatures of an accreting black hole in a globular cluster in the galaxy NGC 4472. *Chandra* has subsequently identified a black hole candidate in a Milky Way globular cluster and further observations are needed to confirm that identification and search for new candidates.

*Chandra* has also provided insights into the X-ray binaries formed by the Universe's first stars. It is not currently possible to detect those first X-ray binaries, but *Chandra* observations have shown that nearby galaxies with properties similar to the first galaxies exhibit strongly enhanced X-ray binary production. This suggests that X-ray binaries dominated the X-ray emission in the early Universe and contributed to the heating of the intergalactic medium (IGM) during the epoch of reionization when the IGM changed from being cold and neutral to being warm and ionized. Future *Chandra* observations, including the upcoming complete survey of galaxies in the Virgo cluster, will drive advancement in our understanding of X-ray binaries.

High spatial and spectral resolution observations of X-ray transients make *Chandra* the telescope of choice for X-ray studies of interstellar dust and gas. Absorption edge spectroscopy of bright persistent sources with the HETG reveals the detailed atomic physics of dust and gas along the line of sight, while studies of dust scattering halos of sources like Cygnus X-1 and Cygnus X-3 constrain the grain size distributions. Over the past five years, *Chandra* has become the premier instrument for X-ray dust tomography. Echoes observed around transient sources like Circinus X-1 and V404 Cygni provide accurate distance measurements to X-ray sources and interstellar dust clouds, making *Chandra* a precision tool to map Galactic structure. In concert with *Swift*, *Chandra* will play a key role in campaigns to follow up future dust echoes.

***Young Stars and Extrasolar Planets***: *Chandra* has also advanced fields where its potential is only now being realized, *e.g.*, in studies of young stars and planetary systems. Direct detection of dusty protoplanetary disks relies on infrared and millimeter observations, but once protoplanetary disks coalesce into planets, the excess emission at infrared and millimeter wavelengths dissipates. Young stars continue to exhibit high coronal activity after planets form, so X-ray observations become the best way to identify young stars once they are a few million years old. *Chandra* is optimized for star-formation surveys because its high spatial-resolution eliminates source confusion and *Chandra's* ACIS imager can detect the hard coronal X-rays that penetrate the neutral gas along the line of sight. The success of these techniques is exemplified by the new *Chandra* X-ray survey of young stars in the Rosette Nebula. When combined with optical spectroscopy, data from HST, *Spitzer*, WISE and ALMA, and anticipated new observations from JWST, *Chandra*'s archival X-ray catalogs of star-forming regions have a great scientific legacy value. Complete surveys of young stars enabled by *Chandra* observations allow us to estimate the lifetimes of disks around stars of various masses, test theoretical pre-main-sequence evolutionary tracks, estimate initial mass functions, star formation efficiency and primordial binary fractions, follow star formation as it propagates through a molecular cloud, and observe stellar clusters as they are born.

*Chandra* is also contributing to the new field of exoplanet characterization and habitability as part of NASA's goal to identify potential sources of life in the Universe. High X-ray fluxes from young stars imply that stellar activity is greatly enhanced at early stellar ages. As the winds from these stars impact the young planet they affect the density and the molecular composition of protoplanetary atmospheres. An active *Chandra* General Observing (GO) program investigates the degree to which X-rays help to dissipate the gas disks around young stars and their planetary systems. *Chandra* has also made important recent contributions to the study of accretion disks in young stars, and has provided the only evidence to date for quasi-stationary shock waves that appear to play a role in collimating stellar jets. The sub-arcsecond resolution of *Chandra* was the deciding factor in separating emission from the collimation shock vs. the stellar X-rays.

This sampling of *Chandra*'s exceptional scientific impact is necessarily incomplete, but it demonstrates the continued importance of *Chandra* as a NASA Great Observatory. Burgeoning new fields as far ranging as multi-messenger and exoplanetary studies gain valuable insights from *Chandra* and specifically leverage the observatory's sensitivity and high spatial resolution. The *Chandra X-ray Observatory* projects good operational health for the next decade and the astrophysics community is poised to exploit it to the fullest for continued scientific discovery.

<u>ADJECTIVAL RATING FOR SCIENCE MERIT</u>: **EXCELLENT**

**CRITERION B: RELEVANCE AND RESPONSIVENESS**

The science portfolio of the *Chandra X-ray Observatory* is highly responsive to all of the strategic priorities identified in the SMD Science Plan and science road map *“Enduring Quests, Daring Visions”*, the NASA Astrophysics Division's Strategic Objectives, and the 2010 Decadal Survey *“New Worlds, New Horizons”*. The scientific highlights described in response to Criterion A can be mapped one-to-one into the Decadal Survey and NASA SMD astrophysics science priorities "**Physics of the Universe; How Does the Universe Work?**" (*e.g.*, gravitational wave and tidal disruption event follow-up, extreme physics of relativistic jets and accretion, dark matter detections and constraints through cluster observations), **"Cosmic Dawn; How Did We Get Here?**" (*e.g.*, observations of high-redshift galaxies and quasars, feedback in galaxies and galaxy clusters, black-hole occupation fractions), and "**New Worlds; Are We Alone?**" (*e.g.*, X-ray observations of transits, stellar activity of dwarfs, star formation and stellar evolution through population studies of stellar X-ray sources, mapping the origin of heavy elements like oxygen, calcium and iron in supernova remnants).

Over the coming decade, *Chandra* will remain the most powerful X-ray telescope in operation, filling a critical need for high-resolution X-ray imaging spectroscopy in the science cases of the 2010 and upcoming 2020 decadal surveys and the NASA Science Plan. Even 20 years post launch, *Chandra* continues to impact newly emerging fields that excite the public: such as exoplanets, neutron star mergers, and the extreme physics around black holes and multi-messenger astrophysics. With the excitement brought to the astrophysics community by the ongoing and anticipated LIGO/Virgo discoveries of new gravitational wave events (such as a neutron star-black hole merger or nearby SN), as well as the Event Horizon Telescope’s most recent and first ever view of a black hole shadow, *Chandra* will remain a core pillar of NASA’s mission to explore the cosmos, answer the call of the scientific community, and educate the next generation of scientists.

The *Chandra* team has made significant progress towards all of the 2016 Senior Review Prioritized Mission Objectives (PMOs) and made major improvements to operations in response to the recommendations of the 2015 Operational Review and the 2016 Senior Review (SR).

In response to PMO-1 of the 2016 SR, the *Chandra* team and the observatory continue to provide outstanding scientific value to a wide range of science areas in astronomy that is highly relevant and responsive to the scientific goals of NASA and the world-wide astronomical community. The entire sequence from proposal to data analysis is well-supported. Data quality, analysis software packages, observation planning and analysis support are all exemplary.

From its inception, the *Chandra* team has fully embraced a commitment to having the overall science program and the science target selection be driven by community input, in keeping with PMO-2 of the 2016 SR. This approach continues to allow *Chandra* to stay at the scientific cusp and maintain the highest level of relevance across fields. It has also resulted in consistently high productivity and impact. The *Chandra* peer review functions smoothly, and the modest amount of observing time committed to Director's Discretionary Time is used in large part to support community requests of time sensitive programs that cannot be accommodated through the regular peer review process. The team's timely and effective implementation of the *Chandra* Cool Targets (CCT) program successfully incorporated community input for new target selection. Additional opportunities for this type of input remain.

The completion of the *Chandra* Source Catalog CSC 2.0 is a major achievement towards PMO-2 of the 2016 SR. The value-added data provided by the CSC 2.0 compared to version 1 make it a much more powerful tool. The *Chandra* team is committed to periodically re-running the pipeline as more data enter the archive, which will keep the catalog relevant especially in light of upcoming large time-domain surveys like LSST that will have to be correlated with existing high-energy source catalogs. The team is committed to providing and improving interfaces of the CSC to major astronomical archives and search tools, such as HEASARC, Simbad, and VizieR.

As outlined in section C of this report, the *Chandra* team is providing excellent stewardship of the observatory, in response to 2016 PMO-3. The *Chandra* team has addressed all recommendations and findings of the 2016 SR in full and provided excellent documentation of their efforts in the 2019 SR proposal. The performance of the flight operations team at keeping the efficiency of the observatory consistently high and preserving spacecraft health is outstanding. The operations team has made major improvements in software and automation, particularly for short term planning and target acquisition, since the 2015 Operational Review and 2016 Senior Review that have had a very positive impact on the ability of the operations team to respond to the increasing complexity of scheduling demands.

In keeping with the recommendations of the 2016 SR, the *Chandra* team has maintained excellent control and understanding of the thermal constraints. The team has been a careful steward of the observatory in regard to the issue of increasing contamination of the ACIS optical blocking filter, involving the entire instrument team and the wider community through representation in the *Chandra* Users Committee.

As noted by the 2016 SR, the buying power of the General Observing (GO) program budget has been seriously eroded by inflation. However, the urgently needed increase to the GO program cannot be at the cost of spacecraft health, operations, or science support, which are operating on an extremely lean budget already.

<u>ADJECTIVAL RATING FOR RELEVANCE AND RESPONSIVENESS</u>: **EXCELLENT**

## CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

***Operating Cost and Cost Efficiency***: *Chandra's* cost plans effectively address the spectrum of technical capabilities required to operate the observatory efficiently while maintaining high scientific productivity. Current and projected costs are reasonable and in line with previous operational costs. *Chandra* has made thoughtful use of available funds, especially in light of the increased resource requirements to operate the mission as the spacecraft ages. The *Chandra* team continues to identify creative ways to optimize available funds, including regular appraisals and improvements to operational processes and procedures. Where possible, automation is being used across the project to respond to increased resource requirements, particularly in the area of mission planning. The unexpected transfer of the Operations Control Center from Cambridge to a new facility in Burlington, MA was implemented seamlessly and without a corresponding increase in budget.

***Budget Erosion by Inflation***: The flat outyear budget profile does not include increases to account for inflation. In order to maintain core operational competencies (flight operations, mission operations) and protect the already flat GO budget, the project has proposed a workforce reduction of 12 staff members over the next 4 years. While streamlined operational processes and increased automation address some cost risk, with the challenges of an aging spacecraft, continued workforce reductions are likely to have a significant operational impact over time. The *Chandra* team is operating at near minimum funding levels. Further workforce reductions in order to meet budget constraints due to inflation are likely to impact the project's ability to maintain operations that meet the needs of the science community.

*Chandra* is to be commended for protecting the GO funding over time; however the lack of inflation adjustment has eroded the buying power of grants by a factor of two since the initial proposal cycle. An inflation-adjusted budget augmentation to preserve the core operational workforce and to prevent continued erosion of GO funding would maintain the overall health and scientific productivity of this unique Great Observatory.

***Health of Spacecraft and Instruments***: *Chandra* has been on orbit for almost 20 years and while there has been some degradation in spacecraft performance, the majority of Chandra's subsystems continue to perform nominally. The *Chandra* team's analysis shows that the *Chandra* spacecraft and instruments are healthy and projected to support a 25+ year mission.

The main issue affecting the health of the spacecraft is degradation of the spacecraft's multi-layer insulation and other thermal protective surfaces. In response, the mission has implemented several creative changes to their operational model to continue producing high value science including improved modeling tools to predict thermal behavior used in short-term scheduling, breaking up long observations into a series of non-contiguous shorter ones, and soliciting a pool of targets used for thermal regulation (the *Chandra* Cool Targets). These changes to mission planning are complex operational adjustments that are made possible by expert staff and new or updated scheduling software.

While thermal issues are expected to have some impact on Target of Opportunity (ToO) and Director's Discretionary Time (DDT) requests, improvements in automation have allowed *Chandra* to continue to respond quickly to all but "Very Fast" requests, which provide some of the most exciting science results from *Chandra*, including the study of the X-ray counterpart of the first neutron star – neutron star merger identified via gravitational waves. *Chandra* has appropriately prioritized protecting flight/mission operations staff and embraced automation where possible. Further reductions in operational staff could negatively affect operational capabilities and the missions ability to deliver unique high-quality science data.

The main issue affecting the health of the instruments is the continued buildup of contamination on the ACIS optical blocking filter (OBF). While the contamination results in a drop in X-ray detection at low energies below about 1.5 keV, this drop in sensitivity does not affect the unique capability of *Chandra* to provide sub-arcsecond imaging.

***Training & Mentoring the Next Generation*****:** The *Chandra* team has been proactive about training and mentoring the next generation of leaders. Deputies have been identified for mission critical positions to ensure knowledge transfer and encourage leadership development. Additionally, as workforce levels have tightened, a number of teams have cross-trained in key areas to reduce risks associated with of loss of critical staff and to address the continued need for experienced workforce to support the longer-term requirements of the mission.

Analysis tool development has emphasized reducing the "barrier of entry" for non-expert users, which enables new *Chandra* investigators and new investigators to Astrophysics. The Chandra Source Catalog CSC 2.0 reduces the barrier of entry even further. The mission has addressed diversity and inclusion concerns. The fraction of proposals submitted by female PIs has grown from less than 20% at the beginning of the mission to about 30% now, which is close to the fraction of women receiving degrees in astronomy. The proposal acceptance rates for males and females are statistically indistinguishable over the past 10 cycles.

ADJECTIVAL RATING FOR TECHNICAL CAPABILITY AND COST REASONABLENESS:
**EXCELLENT/VERY GOOD**

## ADDITIONAL REQUESTED FINDINGS

**1. The effectiveness of the observatory, and its associated operations center and infrastructure in enabling new science, archival research, and theoretical studies.**

*Chandra* is a mature observatory that has been run effectively for two decades and is still delivering outstanding science. *Chandra's* oversubscription rate is still high (5.5 in observing time and 3.5 in proposals; 3818 proposals accepted out of 13,548 total submitted since cycle 1) and the worldwide community of *Chandra* users exceeds 4,300 (non-US PIs make up 30% and originate from 43 different countries) with an increase of ~ 180 new investigators each year. *Chandra* scientists have published more than 7,700 refereed papers, with ~ 450 added each year, and *Chandra* grant funding has supported > 4600 research teams in 46 states since launch. *Chandra* offers a training ground for early career scientists (> 18 PhD theses on average per year; > 3911 students and postdocs trained on new and archival data) and its impact reaches into the public sphere engaging the next generation of scientists, including high school students. Substantial software development and support via the *Chandra* Interactive Analysis of Observations (CIAO) packages make the *Chandra* archives a go-to for scientific investigations and training of new scientists.

The science allocation process through the annual *Chandra* X-ray Center (CXC) peer reviews is highly effective in maximizing the breadth of astrophysical science addressed by *Chandra* – there are no obvious deficiencies in the allocations to any specific science area or proposal size – and the oversubscription factor ensures that strong science is executed. The project's extensive and well-calibrated archive of all the data collected by *Chandra* is heavily used. The recent release of the *Chandra* Source Catalog 2.0 will increase the observatory's archival impact. The *Chandra* Data Archive reported average annual downloads of ~ 18 TB in the past 8 years to sites in ~ 108 countries, with many of these downloads unrelated to proposals or funding in the US. *Chandra's* major and immediate impact upon new fields in astrophysics is illustrated by two examples within the past funding cycle: observing the aftermath of the neutron star merger detected by LIGO and investigating how flares from young stars influence the habitability of proto-exoplanets.

**2. 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 three to five years.**

The efficiency of *Chandra's* science and mission operations processes is extremely high. The team prides itself on rapid data collection and distribution (< 2 days between the observation and delivery of data). They maintain *Chandra's* observing efficiency near the long-term average of ~ 70% (which is the maximum as constrained by the need to protect *Chandra's* instruments while within Earth's radiation belts), while accommodating increasing thermal constraints, the challenges of an aging spacecraft, and a nearly 50% reduction in staffing. To maintain and improve efficiency, the team has reduced the period for scheduling contacts with the spacecraft to enable 2-shift rather than 3-shift coverage, and over the years has implemented a number of strategies involving more automation of data processing and validation. They have also implemented more efficient software tools for mission planning, for analysis of large telemetry data sets, and for modeling the temperature profiles of multiple spacecraft components. The *Chandra* X-Ray Center also produces software tools and scripts that lower the analysis barrier for researchers who are inexperienced with *Chandra* data.

The extensive efforts at understanding and modeling the observatory subsystems' aging have allowed the *Chandra* team to mitigate those effects, mainly the temperature rise due to degradation of the multilayer thermal blankets and other thermal surfaces, through the identification of pitch angles associated with heating and cooling. With this information, the mission planners have developed software tools to aid in the development of the observation plan. In addition, the team anticipated the increased need for targets located at positions that allow for spacecraft cooling, and issued a community call for white papers proposing *Chandra* Cool Targets (CCT) at ecliptic latitudes -40° to +40°, for which observations of an arbitrary subset would have significant science value. During observation scheduling, targets from the CCT may be selected to enable appropriate spacecraft cooling. The *Chandra* mission schedulers have done a truly remarkable job in continuing to produce optimal schedules that take into account all the constraints associated with cooling requirements. These activities have resulted in maintaining excellent observation efficiency.

*Chandra's* main technical obstacle is the deposition of contaminants on the optical blocking filter of one of the two focal plane cameras, the Advanced CCD Imaging Spectrometer (ACIS). The team has done an exemplary job in developing procedures to understand and model this issue. The ACIS filter contamination affects only the low-energy (less than ~ 1.5 keV) X-ray response and shows no indication of degrading the higher energy response. The *Chandra* team continues to closely monitor the situation and to assess risks and benefits associated with potential bake-out options. Although the contamination affects some observations more than others, *Chandra* continues to be highly scientifically productive and is well-positioned to remain so.

**3. 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 *Chandra* management teams at Marshall Space Flight Center and at the Chandra X-Ray Center have provided exemplary stewardship of the observatory throughout the mission lifetime. Their highest priorities are to maximize the scientific return of the observatory while maintaining the health and safety of the instruments and spacecraft. This is evidenced by over 19 years of successful operation of the spacecraft and instruments and by the continued production of important scientific results in the face of increasing challenges due to spacecraft aging and thermal degradation. Throughout the mission, *Chandra* staff have responded to and resolved anomalies, mitigated system degradation to minimize impact to science productivity, prepared in advance for possible future degradation and anomalies, and generally worked to ensure *Chandra's* health and safety. They remain vested in and dedicated to continued long term success and operation of the mission. The cross-training of and multi-tasking by very capable people, along with the development of effective monitoring tools, has mitigated the disadvantages of the nearly 50% reduction in staff since launch.

**4. Notable aspects that would enhance the science return of the mission within its available resources.**

A. *Chandra* is the only X-ray astronomy observatory in the foreseeable future capable of sub-arcsecond resolution science. To retain this crucial capability in NASA's mission portfolio, the SR 2019 panel recommends that the budget be increased commensurate with inflation so that the current staff levels can be maintained and the buying power of GO funding is not further eroded.

B. Targets from the CCT list may occupy 10% of *Chandra's* observing time. To maximize the scientific return from the cool targets, a mechanism could be implemented for the regular evaluation and addition of new cool targets.

C. Going forward, there will be a great demand for coordination between *Chandra* and a number of transient-optimized surveys (LSST, ZTF, LIGO-Virgo, etc.). The *Chandra* staff could proactively gather input from these communities in order to maximize the synergy between *Chandra* and these facilities.

D. The reduced transmission at low energies of the ACIS optical blocking filter continues to be a concern, so the possibility of baking out that filter at some point rightfully remains a consideration.

E. *Chandra* could consider a number of mission-directed observations that are selected as a contribution to its final science legacy.

F. While detailed close-out planning for the mission is premature, there may be value in considering some longer-term decommissioning decisions such as increasing collaborative / open source software development with the community, transfer of the *Chandra* Data Archives to HEASARC and the eventual archival home for community data analysis tools and software.

# 2019 Astrophysics Senior Review

## Rest-of-Missions Report

# 2019 Astrophysics Senior Review - Rest-of-Missions Report

**April 29-May 2, 2019**

**PANEL:**

Dr. Alison Coil, University of California San Diego
Dr. Megan Donahue, Michigan State University
Dr. Jonathan Fortney, University of California Santa Cruz
Dr. Mark McConnell, University of New Hampshire / Southwest Research Institute
Dr. John O'Meara, Keck Observatory
Dr. Mike Nowak, Washington University in St. Louis
Dr. Rebecca Oppenheimer, American Museum of Natural History
Dr. David Weinberg, The Ohio State University **- Chair**

## 1. MISSIONS AND BUDGETARY SCOPE

The Rest-of-Missions (RoM) panel of the 2019 Astrophysics Senior Review evaluated six missions, two of which are being considered in Senior Review for the first time. These missions are listed below along with launch date and the “baseline” (FY21 is chosen for illustration) and average yearly “enhanced” budget requests.

We use the terms “baseline” and “enhanced” synonymously with “in-guide” and “over-guide” as described in the proposals, but with two exceptions. Following NASA input, NICER (which is still in its prime mission) submitted a minimal operations budget as “in-guide,” and a budget including guest observer funding as “over-guide.” In the panel’s view, in order to facilitate cross-comparison it is more consistent with other missions to treat the “over-guide” NICER budget as baseline. Conversely, Fermi identified its under-guide budget as “recommended”; the panel regards this budget as the Fermi baseline, and the in-guide budget as enhanced. The FY21 total for the baseline requests is $50.2M, and the enhanced requests would add a total of $2.5M.

| **Abbreviated Name** | **Full Name** | **Launch Date** | **FY21 baseline request ($M)** | **Yearly Delta of enhanced budget ($M)** |
|---|---|---|---|---|
| XMM-Newton (ESA mission) | X-ray Multi-Mirror Mission-Newton | 1999 | 3.5 | 1.1 |
| Swift | Neil Gehrels Swift Observatory | 2004 | 5.6 | 0.3 |
| Fermi | Fermi Gamma-ray Space Telescope | 2008 | 13.8 | 0.4 |
| NuSTAR | Nuclear Spectroscopic Telescope Array | 2012 | 8.4 | 0.3 |
| NICER | Neutron star Interior Composition Explorer | 2017 | 4.9 (incl. $2.5M GO program) | -- |
| TESS | Transiting Exoplanet Survey Satellite | 2018 | 14.0 | 0.4 |

*Table 1: Missions reviewed by the Panel, ordered by launch date. The FY21 baseline budget request is provided as an illustration of mission operation cost. The final column gives the yearly average difference between the baseline and enhanced budgets. Because we take the NICER “over-guide” budget as baseline for the purposes of cross-comparison, there is no enhanced NICER budget in this table.*

## 2. OVERALL FINDINGS

**The Panel finds no scientific reason to discontinue or substantially reduce the funding or scope of any of the six missions under review.**

All six of these missions are producing high-impact science across a broad range of topics, and all of them are functioning well technically with no major risks foreseen over the next five years. Each mission submitted a high quality proposal, fully responsive to the call, gave exciting and informative presentations to the panel, and answered our questions. Although there are overlaps in wavelength range, these missions have complementary capabilities that make them an effective portfolio for addressing many of the highest priority questions in contemporary astrophysics. **We strongly encourage NASA to continue operation of all of these missions and to fund them at a level similar to or higher than their baseline budget requests.**

In all cases the over-guide budgets would address genuine needs and opportunities and would increase each mission's science return. We recommend funding these over-guide budgets to the extent feasible within the overall APD funding envelope. We provide specific prioritization recommendations on over-guide funding below. These recommendations are informed by, but do not strictly follow, our overall ranking of the missions, as the benefit-per-dollar of individual over-guide elements varies.

**The complementarity of these missions makes the overall capability of the portfolio more than the sum of its parts, especially with regard to emerging opportunities in time-domain and multi-messenger astrophysics.** We discuss these complementarities and opportunities further below, and we note some instances where greater communication and cooperation between missions could further their effectiveness.

The Swift mission has been exceptionally effective in building a large user base that pursues a broad range of science, in providing tools that make it easy to propose Swift observations and to use the resulting data, and in re-envisioning the mission over time to maximize its overall contribution in combination with other facilities. For a new mission, TESS has been extraordinarily successful in building a large community of scientists who are engaged in and contributing to their science goals. We commend these missions for their community engagement and recommend that other missions look to them for general strategies, and in some cases for tools that they can adapt to their own needs.

### 3. RANKING METHOD AND RESULTS

After the presentations by and thorough discussion of all six missions, the Panel members separately and anonymously rated each mission, on a numerical scale tied to the adjectival rankings Excellent, Very Good, etc., on each of the three review criteria, as described in the Call for Proposals. The scores from the eight panel members were averaged to produce initial numerical ratings on each criterion, and these were combined with the weighting of 50% to Criterion A, Scientific Merit; 25% to Criterion B, Relevance and Responsiveness; and 25% to Criterion C, Technical Capability and Cost Reasonableness, to provide an overall numerical rating. These numerical ratings were then converted to adjectival ratings. In a few cases where the numerical rating was close to a boundary between adjectival ratings, the panel decided by majority vote which adjectival rating to assign. We note that using median scores from the panel members instead of mean scores would have produced similar results. For reference, the review criteria, adjectival ranking definitions, and relation between numerical scores and adjectival rankings are given in Section 8 of the Call for Proposals.

The overall numerical scores were taken as the basis for the ranking of missions. Given the closeness of some of these scores, panel members were allowed to propose reorderings, which were discussed and decided upon by majority vote.

The adjectival ratings are given in Table 2 below, which is ordered by overall ranking with the highest ranked mission at the top.

| **Mission** | **Criterion A** | **Criterion B** | **Criterion C** | **Overall Score** |
|---|---|---|---|---|
| TESS | E | E | E/VG | E |
| Swift | E/VG | E | E | E |
| Fermi | E/VG | E/VG | VG | E/VG |
| NICER | VG | E/VG | E/VG | E/VG |
| NuSTAR | E/VG | VG | E/VG | E/VG |
| XMM-Newton | VG | E/VG | E/VG | E/VG |

*Table 2: Ranking of missions considered by the Rest-of-Missions Panel, with the highest ranked mission at the top. The ranking is based on the overall score, which is itself based on a weighted average (Criterion A at 50% and Criteria B and C at 25% each) of the panel's average numerical scores in the three categories. Numerical scores have been converted to adjectival equivalents as described in the text. Based on the overall numerical scores, the panel categorizes TESS and Swift as Tier 1 and Fermi as Tier 2. The final three missions, which have very similar overall scores, comprise Tier 3.*

The Panel would like to emphasize several points about these results.

First, every criterion and overall score for every mission is in the range “Very Good” to “Excellent.” All of these missions are technically sound, producing high quality science, and each is led by a strong and engaged team.

Second, our overall numerical rankings (not reported here) fell into three groups, with TESS and Swift in Tier 1, followed by Fermi in Tier 2, and with NICER, NuSTAR, and XMM-Newton very close to each other in Tier 3.

TESS and Swift have both been exceptionally effective at building a broad user community, and each is positioned to make pivotal contributions to rapidly transforming fields: exoplanets in the case of TESS, and gravitational wave and high-energy neutrino astrophysics in the case of Swift. Fermi is similarly poised to play a pivotal role in gravitational wave and high-energy astrophysics. The three pointed X-ray missions have distinct and complementary strengths in sensitivity, energy range, and timing capability, making a powerful combined portfolio.

## 4. DISTINCTIVE STRENGTHS OF THE MISSIONS

We provide detailed assessments of the individual missions at the end of this report. Here we briefly summarize the distinctive strengths that make them an effective portfolio.

**TESS** – The ultra high-precision and high cadence photometry of bright stars makes TESS an extraordinary new resource for transiting exoplanet science and for stellar astrophysics through asteroseismology. The longer total time baseline and the shift to 10-minute cadence for full frame images promise to make the extended mission even more powerful than the prime mission.

**Swift** – Swift provides a wide field of view in its Burst Alert Telescope and the ability to slew rapidly to observe targets of opportunity at X-ray and UV/optical wavelengths. It provides time-series photometry for a wide range of sources. These capabilities are especially valuable for gravitational wave and multi-messenger astrophysics.

**Fermi** – Fermi provides unique access to the gamma-ray spectrum, and the largest simultaneous field of view of any space telescope. It provides a time-domain view of the entire gamma-ray sky and is another crucial asset for gravitational wave and multi-messenger astrophysics.

**NICER** – NICER has the largest effective area for soft X-ray spectroscopy of any operating mission, rapid slew capability, and millisecond-level timing capability. These capabilities are essential to its prime mission objective of constraining the masses and radii of neutron stars, and they make NICER a powerful asset for many other X-ray astronomy applications.

**NuSTAR** – NuSTAR is the first focusing hard X-ray mission, with unprecedented sensitivity at 10-80 keV energies and high spectral resolution. This hard X-ray sensitivity is crucial for understanding a wide range of astrophysical phenomena including the hot coronae of accreting black holes, the sources of the cosmic X-ray background, and the properties of ultra-luminous X-ray sources.

**XMM-Newton** – Two decades after launch, XMM-Newton remains (along with Chandra) one of the world's premier general purpose X-ray facilities, with good imaging and excellent spectroscopic capabilities, especially at soft (0.2-2 keV) energies. It is the most powerful facility for studying diffuse hot gas in galaxy groups, clusters, and the intergalactic medium. Because XMM-Newton is operated by ESA, all NASA funding goes directly to support of US investigators making the science-per-dollar return of XMM-Newton exceptionally high.

It is notable that five of these six missions operate in the X-ray or gamma-ray regime, as does Chandra (not considered by this panel); TESS is optical, and Swift and XMM-Newton have UV imaging capabilities. This wavelength concentration is complementary to the capabilities of Hubble, JWST, and SOFIA. TESS, Swift, and Fermi have large instantaneous fields of view, while NICER, NuSTAR, and XMM-Newton primarily use pointed observations. The next SMEX and MIDEX missions, IXPE and SPHEREx, will provide new and complementary capabilities in X-ray polarimetry and in wide-area near-IR spectrophotometry, respectively.

## 5. CONTRIBUTIONS TO TIME-DOMAIN AND MULTI-MESSENGER ASTROPHYSICS

Time-domain astrophysics and connections to gravitational wave and/or high-energy neutrino detections were central themes of the panel discussions and arose as considerations for all of the missions. The roles of Fermi and Swift in providing early data on the GW170817 binary neutron star merger and the TXS 0506+056 blazar outburst associated with an IceCube neutrino event are two of the highlights of the field of multi-messenger astrophysics to date, and harbingers of the opportunities ahead.

Multi-wavelength observations of gravitational wave events are expected to be an especially high-impact area over the 5-year span covered by this Senior Review. The different missions have different roles to play in this field, in localization, detection of prompt emission (e.g., short GRBs), characterization of early emission, and observations over extended periods.

The Swift Burst Alert Telescope (BAT) and the Fermi Gamma Ray Burst Monitor (GBM) are the two instruments that can potentially detect gamma-ray transients shorter than a few seconds that are associated with compact object mergers. The GBM instantaneously observes about half of the sky, and it localizes detected sources with an accuracy of a few degrees. The BAT has an instantaneous field of view of about ⅙ of the sky and higher localization accuracy of roughly 3 arcminutes. If BAT is able to detect a gamma-ray transient, then it immediately provides a localization adequate for follow-up by any facility. A Fermi GBM detection provides localization considerably better than typical LIGO/VIRGO error boxes but large enough to require further scanning. The GBM observes the full sky every orbit, and the Fermi Large Area Telescope (LAT) observes the full sky every two orbits, so either could provide an early detection and few degree localization if the event produces sufficiently bright gamma-ray emission.

In the absence of a prompt detection, the Swift X-ray Telescope (XRT) is the most effective instrument for space-based localization because it can rapidly scan through a list of previously known galaxies that lie in the LIGO/VIRGO error box and the correct redshift range, or it can conduct an area scan weighted by host galaxy probability.

- Given a tight localization from space or ground, Swift is the instrument that can most rapidly respond and get early-time X-ray and UV light curves. NICER also has fast slew capability, which could be a major asset for early-time X-ray spectroscopy if its ToO response mechanisms are improved along the lines described in the NICER proposal. NuSTAR and XMM-Newton can respond on a somewhat longer timescale to monitor the evolving X-ray spectrum over a wide energy range. The Fermi LAT will automatically provide a gamma-ray light curve (or upper limits) for any gravitational wave transient as it scans the sky every two orbits.

The odds of any individual transient falling within the contemporaneous TESS observing area is only about 6%, but given the pace of recent gravitational wave detections there is a significant chance of getting one or more neutron star mergers within a TESS sector over a 3 year span. In this case, TESS will automatically provide high-cadence optical light curves before, during, and after the merger event, like the superb early-time light curve data it has already provided for a number of supernovae and the recent tidal disruption event.

Fermi and Swift data effectively increase the search volume for gravitational wave events associated with gamma-ray transients, since the signal-to-noise threshold for the gravitational-wave detection can be lowered at the locations and times of these transients.

Each of the missions is paying careful attention to opportunities in time-domain astronomy in general and to gravitational wave event follow-up in particular. However, there is not yet much attention to a coordinated approach or sharing of tools among missions. Given the high priority and rapidly evolving landscape of this field, **we recommend that NASA convene a meeting of mission leaders (e.g., PIs or Project Scientists) to foster development of a coordinated strategy, communication, and shared tools for electromagnetic observations of gravitational wave events or other rare transients of high scientific importance.**

The recently formed NASA Gravitational Wave–Electromagnetic Counterpart Task Force may provide a natural forum for developing these strategies and tools. It would be beneficial for this task force to host a focused meeting with leaders of the missions discussed in this report.

Many of the issues and opportunities for high-energy neutrino astrophysics parallel those in gravitational wave astronomy.

## 6. TRAINING FOR THE FUTURE

The Call for Proposals for the 2019 Senior Review asked proposals to address: “In the context of the expected lifetime of the mission, the project’s plans to prepare for the future by providing the training, mentoring and leadership opportunities that will expand the skills of its staff, as well as foster the next generation of mission leaders.”

This review was the first Senior Review to include such a request, and the responses to it ranged in quality and were generally below the panel's expectations. For the 2022 Senior Review, the panel suggests that NASA call out as distinct elements of a desired response:

1. The project's succession planning and the elimination of single points of failure for the leadership and support of their own mission;
2. The ways that the project provides opportunities for and mentoring of the next generation of mission leaders and mission scientists; and
3. The project's strategies for broadening its community of users and training a diverse community of astronomers to make effective use of space-based astrophysics data.

We consider all three of these elements to be implicit in the language of the Call for Proposals, but most missions addressed primarily the third item and to a lesser degree the second.

Examples of effective strategies described to the Rest-of-Missions Panel include: (a) the Fermi mission's encouragement of postdocs to lead scientific working groups as a way to build experience in collaboration leadership, and (b) the TESS mission's extensive involvement of early career scientists in leading GI programs and data validation efforts. Other effective strategies could include supporting postdocs and other early-career scientists to contribute to and speak in high-level presentations (such as the Senior Review, as done this year by the NICER team) or encouraging them to participate in writing white papers for efforts such as the 2020 Decadal Survey.

The panel recommends that missions participating in the 2022 Senior Review pay careful attention to this element of the review in their proposals and presentations.

## 7. IMPORTANCE OF GO/GI FUNDING

In addition to our charge of giving guidance to NASA on the scientific priority of the missions, we would like to highlight the importance of the GO/GI programs in each of these missions. Science funded from GO/GI programs has significant impact, not only on the specific fields of interest, but on the missions themselves. Many missions have, over time, adjusted their operations and capabilities in direct response to new discoveries by GO/GI funded members of the community. The Rest-of-Missions Panel notes that in many cases the average funding award in a GO/GI program has dropped below the level needed to fund a graduate student for an academic year.

The total request for GI/GO funding in the baseline budgets presented to the Rest-of-Missions Panel amounts is approximately $16M/year, with approximately an additional $2M/year requested by the missions in their enhanced budgets (again, the Panel regards the NICER GO program as part of its baseline budget). This additional number, compared to the total portfolio budget, presents a significant opportunity for a large return on investment in science from the community. As in previous Senior Reviews, the sense of the committee is that increases in GI/GO funding should be realized if there is flexibility in the top-level budget. Decreases in the GI/GO budgets for any of the missions relative to baseline would have a negative impact on science return, and the panel recommends that they be avoided if possible.

## 8. BUDGET ENHANCEMENT RECOMMENDATIONS

The panel's recommendations for specific mission enhancements are prioritized not necessarily by the overall ranking described above. Here we outline why. The order of priority is indicated in the order of the paragraphs below, with highest priority first. For items that are not specifically mentioned in the following six paragraphs, NASA should use the mission ranking above.

1. The NICER mission, in particular, is the highest priority for full over-guide funding, as it moves from prime into extended phase. In this case, implementing the lower level of funding means that NICER will not be broadly available to the community, with no GO program. Operating NICER without a GO program would be contrary to the spirit and primary purpose of extended missions to enable broad use of these national assets by people other than just the original mission scientists. The panel also puts high priority on the augmentations needed to enable faster and more systematic ToO response, both to MAXI triggers and to ground-based alerts.

2. For TESS, additional GI funding is recommended, as this mission is also moving from prime to extended phase. The prescient (and inexpensive) request to continue full modeling of the attitude control system is also strongly recommended, to permit changes in operations as the system ages. This is particularly useful given the experience of Kepler's transformation into the K2 mission due to the loss of part of the pointing system. While K2 managed to solve that problem with wonderfully creative engineering, preparing for pointing

issues in the case of TESS is recommended and is a two-year effort that could enable changes in the TESS mission in the future.

3. For XMM-Newton, the entire funding profile is for software and GO support. The panel recommends the budget enhancements to the GO program, as they are likely to increase the US science return from this flagship-class mission. The funding for software would only impact a small minority of the community, so it is deemed less important.

4. For Swift, the API for ToO requests and the UVOT software tool to automate light curve generation are recommended. The motivation for the Las Cumbres Observatory GO augmentation is not thoroughly justified in the proposal, so the panel gives it lower priority. Since Swift is our second-ranked mission, enhanced GO funding is desirable if the APD budget allows, but it should not necessarily be tied to the LCO program.

5. For NuSTAR, the panel recommends total funding near the in-guide level. The panel further recommends that some cost savings described in the under-guide budget, in particular regarding reduction of continuing support for the legacy programs, be utilized to support elements of the over-guide proposal, in particular the thermal analysis and updates to the background modeling tool. The expanded ToO support is also deemed to be beneficial and worth implementing if possible.

6. The Fermi proposal listed (relatively minor) reductions to their operating budget in their “recommended” budget, though they described this budget as “under-guide.” The panel concurs that these operating efficiencies should have only minor impact on science return and are appropriate given the stage of the Fermi mission. We recommend adopting this budget as the Fermi baseline and including the enhanced GI funding requested in the in-guide budget if APD finances allow.

If these enhancements are not feasible within the APD budget and cuts are necessary instead, the first course of action should be to adopt the baseline budgets for all of the missions instead of any of the enhanced budgets. As previously noted, the panel regards the over-guide budget submitted for NICER as baseline and the under-guide budget submitted for Fermi as baseline. This first course of action should also include the reduction in support for the NuSTAR legacy program described in bullet 5 above.

If further cuts are needed, the second course of action is to seek further savings in Fermi operations, since this mission has been operating for over a decade and still has an expensive operations budget. These savings would come at a cost in science capability; retaining capabilities that support gravitational wave and multi-messenger astrophysics are the highest priority.

If still further cuts are needed, then APD should make proportional reductions in all of the GO programs, rather than retaining some and eliminating others entirely.

# Rest-of-Missions Report

# Individual Mission Evaluations

# Fermi

**SUMMARY OF MISSION AND PROPOSAL**

Fermi is a gamma-ray mission with two instruments, the Gamma-ray Burst Monitor (GBM, 10 keV – 30 MeV) and the Large Area Telescope (LAT, 20 MeV – 300 GeV). The GBM instantaneously monitors the entire visible sky and views the full sky once every orbit. The LAT monitors 20% of the sky at any one time while sweeping the entire sky every 3 hours. This sky coverage is not just extraordinary at gamma-ray energies, it is unique – especially that of the GBM – across the electromagnetic spectrum. Fermi was launched in 2008 and is now in its 11th year of operation. The Fermi team proposed an FY2020 $13.6M budget that is reduced from its baseline budget of the previous year, identifying cost savings in operations while increasing support for its GI grants to $3M. The increase to $14.1M in FY2024 reflects flat FTE and GI funding, with annual increases in personnel costs. The requested augmentations are about $200K/year in GO funding and $400K/year in operations/development.[1]

**CRITERION A: SCIENTIFIC MERIT**

The unique features of the Fermi gamma-ray mission, including its sky coverage and huge energy span (8 decades in photon energies), have allowed it to continue its scientific productivity of past years and be at the forefront of some of the most exciting astronomical discoveries of the last few years. In particular, these capabilities allowed the GBM to detect the short-duration gamma-ray burst (GRB 170817A) 1.7 seconds after the LIGO detection of gravitational waves from the merger of two neutron stars (GW170817), and the LAT to identify the blazar TXS 0506+056 as the source of an ultra high-energy neutrino identified by the South Pole IceCube neutrino experiment. The future monitoring of the gamma ray sky will continue to yield new discoveries of this type; as the LIGO, VIRGO, and the Japanese Kamioka gravitational wave observatories improve their sensitivities, other gravitational observatories are built, and as existing neutrino and high-energy cosmic ray observatories continue and upgrade their own operations. All of these multi-messenger observations benefit from knowing what the gamma-ray sky is doing as none of them localize individual events very well on their own. Gravitational wave events will occur within the Fermi coverage, including possibly

[1] In the Fermi proposal, the “under-guide budget” was their recommended budget. Their “in-guide” budget included the enhancements.

neutron star-black hole mergers and short gamma-ray bursts associated with neutron star mergers, regardless of expectations of whether or not such events will emit electromagnetic radiation. These observations and the other scientific efforts of Fermi (e.g. surveys of pulsars, binary supermassive black hole searches) test and expand our understanding of fundamental physics, general relativity, and the physical processes (relativistic particle acceleration, relativistic magneto-hydrodynamics) associated with extreme objects and events.

As part of the NASA portfolio, Fermi is the only mission that covers the MeV-GeV range and is the most prolific gamma-ray burst detector. The team proposes to improve and speed up its identification of fainter, less significant GBM events, which will improve its utility in identifying, confirming, studying, and localizing gamma-ray counterparts to gravitational-wave events. The LAT all-sky catalog now includes over 5000 sources, and they propose a light curve tool to allow astronomers to extract a decade of temporal behavior for gamma ray sources. One example of the synergy between operating missions in the current NASA portfolio comes from the discovery of the first ultraluminous X-ray pulsar, SWIFT J0243.6+6124. The complete characterization of this system required data from Fermi/GBM, Swift/BAT, NICER, NuSTAR, and Gaia.

Fermi's data and user support for data analysis have been improved over the history of the mission. The 2015 major update to the LAT processing (Pass 8) went well except for one event-classification aspect (some cosmic rays were misidentified as gamma rays), for which a repair was subsequently developed. Suitably reprocessed data were released in Nov 2018, and any current data are processed with the updated version. The mission provides python-based analysis tools (GSPEC, Fermipy) in addition to the Fermi Science Tools. All data are made public immediately after processing; the data are available within a day and usually sooner.

One recent example of the use of the data archive was the estimate of Hubble's constant ($H_0$) based on redshift-independent distances estimated from the gamma-ray attenuation of 700 blazars.

## CRITERION B: RELEVANCE AND RESPONSIVENESS

Fermi is highly relevant to the objectives and focus areas of the SMD Science plan. It was the top-ranked medium-scale mission in the 2001 Decadal Survey. Current Fermi science addresses two of the three priority science objectives identified in the 2010 Decadal survey: (1) "searching for the first stars, galaxies, and black holes" by discovering GRBs, and (2) "advancing understanding of the fundamental physics of the universe" by enabling our study of astrophysical jets, sources of relativistic particles, and endpoints of stellar evolution. Fermi addresses the primary goal of the 2018 SMD science plan to understand the universe. Indeed, the 2013 Astrophysics Roadmap recognizes the Fermi mission for its studies of supermassive black holes and pulsars. The detection and characterization of the "Fermi bubbles" in our own Milky Way captures the history of energetic behavior, and possible influence (feedback) into the halo gas its environment by the supermassive black hole in the center of our own Galaxy.

Table 1 of the Fermi proposal documented considerable progress against their 2016 Senior Review goals. Progress was reported for all of the stated goals. The dark matter searches and papers are still in progress, as is work on the Pass 8 instrument responses.

The RoM panel commends the Fermi team on a successful transition after the reduction of the Department of Energy funding, and the relocation/reorganization of the LAT instrument support from Stanford to Goddard Space Flight Center. Furthermore, the GSFC Flight Operations Team has successfully emerged from a change in contract.

**CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS**

Fermi is in good health. The LAT and GBM are healthy, with no signs of degradation in performance. It did experience a failure of one of the Solar Array Drives, which prevents one of the solar arrays, still functional, from moving. This failure did not affect the observing efficiency, but one worry is that the one remaining drive could fail and leave the observatory in a severely compromised state. Two modes of observing - the traditional mode, where the LAT is pointed 50 degrees above the orbital plane for one orbit and 50 degrees below for the next one, and sinusoidal mode, where the the position rocks slightly, to keep the x-side of the spacecraft (with the solar array) pointed at the Sun - are now used. Furthermore, it is possible that if the 2nd SADA failed this two-mode approach could be adapted to minimize science impact.

The high cost of data processing and pipelines was striking to the review panel, and the cost appears to be coming from the number of FTEs working around the clock. Reduction of the human effort required in meeting the expectations of low-latency data, especially LAT data, would seem like a natural line of approach for finding further cost efficiencies in future years.

**Recommendation:** A NASA operations review of Fermi, including its data processing pipelines software and management, should be conducted to explore possible efficiencies and automation for monitoring the pipeline and instrument status. This review should assess when low-latency response to new data is essential to the scientific value of the extended mission (e.g., to aid in localization of gravitational wave events) and when it is desirable but not essential.

The Fermi team is doing a good job in mentoring and developing the future leaders of astronomy. The review panel commends their 8 years of hosting a summer school for graduate students to work on Fermi data, and their policies for supporting early-career team members to take scientific leadership positions for the working groups on the team.

## OVERALL ASSESSMENT

Fermi remains unique as a true all-sky monitor, operating in an important energy band that is not adequately covered by other missions. It undoubtedly will continue to play an important role in both multi-messenger and time domain astronomy. Additionally, it has unique synergies with other instruments not replicated in the remainder of the NASA portfolio. The Fermi mission continues to provide a steady stream of important scientific results. Its synergy with LIGO/VIRGO and IceCube should not be underestimated. It also plays an important complementary role for ground-based atmospheric Cerenkov instruments, such as Veritas, MAGIC, and the upcoming CTA. Because it surveys the sky several times per day, it provides a data archive that will continue to be useful for a wide range of multi-wavelength and multi-messenger studies. Although there are some concerns about the health of the spacecraft (namely, the remaining SADA), the overall mission remains healthy. The Fermi team is taking steps towards broadening the usability of the instrument, e.g., via creating an improved pipeline for generating AGN light curves, and making it easier for users to generate data products. The panel recommends that further economies be pursued.

The proposed over-guide augmentation to the GI program and augmentation towards the development of software tools both seem reasonable, and should be funded as budget and balance allows.

# NICER

**SUMMARY OF MISSION AND PROPOSAL**

NICER is an instrument externally mounted on the International Space Station (ISS) that provides spectroscopy and timing of sources in the X-ray range from 0.2–12 keV. It operates much like a collimated instrument, in that it is a non-imaging instrument with a small FoV about 6 arcmin across. A unique feature of NICER is the ability to track specific sources across the sky (as seen from ISS), and to rapidly slew between targets. It typically tracks between 3 and 6 sources per orbit and has amassed a total of nearly 12,000 observations of 350 distinct targets.

With its successful launch and installation on ISS in 2017, NICER has embarked upon an exciting science program. NICER-related publications are already on track to become the largest number of peer-reviewed science papers of any ISS-hosted instrument. Current publication totals may be modest (21 peer-reviewed papers so far, with 50% more under review), but this is comparable to rates from other small missions at a similar, relatively new stage of their mission lifetime.

Compared to the last NASA-led mission dedicated to rapid X-ray timing, the Rossi X-ray Timing Explorer (RXTE), NICER offers timing resolution that is 50x better, an energy resolution that is 10x better, an angular resolution that is 10x better, a sensitivity that is 20x better, and inclusion of the 0.2–2 keV bandpass that was not covered by RXTE. These capabilities open up a range of sources, especially extragalactic objects, that were either inaccessible or extremely difficult to observe with RXTE. The large effective area, low background, narrow field of view, with good spectral resolution, also make NICER a powerful instrument for spectral/timing studies of point sources for which Swift might lack the effective area to adequately observe or XMM-Newton might lack the flexibility to follow. NICER is thus highly complementary to the overall NASA portfolio of observatories.

NICER did not propose an in-guide budget. They provided a notional budget that would continue the mission operations at current levels. An over-guide budget provided additional resources for a new guest observer (GO) program and the development of a more rapid ToO response capability.

**CRITERION A: SCIENTIFIC MERIT**

The NICER team identified three science objectives for its prime mission, all of which focus on our fundamental understanding of neutron stars. These objectives focused on neutron star structure (to reveal the nature of matter within neutron stars), neutron star dynamics (to probe the physics of dynamic phenomena), and neutron star energetics (to infer how energy is extracted).

NICER has already made significant progress in several areas. For example, light curve modeling of the thermal emission from rotation-powered MSPs has provided constraints on the neutron star equation of state (via measurements of the mass-radius relationship). It has also made important contributions to the study of the first known ULX source in our galaxy (Swift J0243.6+6124). The joint spectral/timing capabilities of NICER open up new possibilities in dynamic studies of astrophysical sources. One exciting example is the X-ray reverberation mapping of accretion disks in compact object systems.

The data are typically made available from HEASARC within two weeks of data collection. This is driven largely by a two week verification period. Guest observers can request an exclusive use period, which is sometimes (though not always) granted. The panel expressed some concern about the lack of maturity of the analysis tools, especially the background modeling. Providing these tools, along with publicly available guidance on their use, is viewed by the panel as important for growing the NICER user base and enhancing its scientific impact.

Significant efforts have been made to develop partnerships and to coordinate observations with other observing facilities, both ground- and space-based. The space-based facilities include missions in the NASA portfolio (NuStar, XMM, Chandra, Swift, and HST), along with foreign missions (INTEGRAL, ASTROSAT, and Hisaki). Ground-based partners include both optical and radio observatories. These collaborative efforts are crucial to expanding the scientific impact of NICER.

## CRITERION B: RELEVANCE AND RESPONSIVENESS

The NICER mission, especially its X-ray timing capabilities, is well aligned with NASA strategic goals to “probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter, and gravity” as well as “explore the origin and evolution of the galaxies, stars, and planets that make up our universe.” NICER is well-designed to study the innermost, relativistic regions around black holes and neutron stars, and therefore serves as a unique probe of strong gravity physics, nuclear equations of state, and extreme states of matter. Its potential for rapid response and flexible pointing will also allow it to play an increasingly important role in the continued expansion of time domain astronomy.

The NICER soft X-ray response, rapid timing capabilities, and flexible pointing capabilities makes it synergistic with both ground based optical initiatives, such as the Large Synoptic Survey Telescope (LSST) and the Zwicky Transient Facility (ZTF), and NASA facilities, including hard X-ray and gamma-ray facilities such as NuSTAR and Fermi. NICER has implemented a cooperative agreement with NuSTAR to provide NICER time in the NuSTAR GO program, and to allocate NuSTAR time in the NICER GO program. NICER (along with all currently operating high energy instruments) is also an active participant in the International Astronomical Consortium for High Energy Calibration (IACHEC).

The NICER mission was not part of the 2016 Senior Review and therefore did not have Prioritized Mission Objectives (PMOs) to address from this prior review. Instead, the panel considered progress towards prime mission goals and the proposed PMOs for this Senior Review.

As noted in the proposal, the 2015 NASA Technology Roadmap identifies pulsar-based navigation and X-ray communication as revolutionary concepts. NICER has successfully demonstrated autonomous navigation using pulsar timing. Furthermore NICER is providing their modulated X-ray source (MXS) methods used for their timing calibration to the ISS as part of a technology demonstration for the first space-based X-ray communication demonstration. In terms of the NICER prime mission science of modeling pulsar light curves to constrain neutron star equations of state, both the proposal and the presentation to the Senior Review demonstrated impressive progress towards this goal.

NICER has proposed three PMOs to this Senior Review: further observations in support of NICER Legacy Science (pulsar timing, additional observations to further constrain neutron star equations of state, support of time domain and multi-messenger astronomy), establishment of a GO program (a Cycle 1 program has already been partly implemented), and faster response to targets of opportunity (ToO). All of these goals were viewed as worthwhile, and the RoM panel judged the latter two as being especially important. Establishment of a GO program will allow for increased opportunity for the scientific community to help direct the science priorities of the mission. The specific plans to improve the responsiveness of NICER to ToO not only will enhance the mission's scientific output, but they also may help to increase operational efficiencies and improve the cost effectiveness of mission support.

**CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS**

One of the primary features of NICER is its schedule flexibility and rapid slewing capability. These features provide the potential for an instrument with rapid response to ToOs. However, the current responsiveness is more limited than it could be – up to four hours during business hours (although sometimes as short as a few minutes) and up to 72 hours otherwise. Given the design of the instrument, one would expect the hardware could be capable of routinely responding within minutes, perhaps even seconds. The panel feels that an improvement in ToO response is critical to the long-term value of the NICER mission.

The current ToO response process requires considerable human intervention. This is a cumbersome and ineffective process, in part because it requires trained personnel to be on-site for generating and issuing commands. To the extent possible, humans should be removed from the decision process. The NICER team has developed a detailed plan to provide a direct connection to the MAXI instrument on ISS and to use their transient detection capability to develop an automated ToO response system. Triggers from MAXI will be ingested by on-board software and evaluated in terms of their scientific interest.

Establishing a response capability with MAXI is an excellent idea. The RoM panel strongly believes that once a rapid response capability is established using the MAXI connection the NICER team should seek to further expand this capability to encompass use of other automated triggers, such as GCN notices. Given the plethora of transient detections that can be expected in the coming years (especially with the onset of ZTF and LSST), an enhanced ToO capability would represent a significant enhancement to the NICER mission. The panel suggests that the NICER team develop an active relationship with the Swift team and other groups with experience in developing pipelines and routines for responding rapidly to targets of opportunity.

The first GO Cycle competition has just recently been completed. A total of 84 proposals were submitted (58 of which were from US PIs), of which 49 were accepted (36 from US PIs). The panel expressed some concern about the modest response to this solicitation and felt that the NICER user community could be greater given the potential of the instrument. More should be done to develop broad community awareness of the NICER mission. The NICER team noted that they had a significant representation at the recent HEAD meeting.  The NICER team should look for opportunities to interact with the broader community beyond the HEAD meeting.

The panel supports funding the NICER program at the over-guide level in order to provide funding for a GO program and to support improvements of the efficacy of ToO response.   A GO program is crucial to the success of the mission and should include support for guest observers. As noted in earlier sections of the report, the panel considers the budget submitted as “over-guide” for NICER to be better characterized as “baseline,” since it is similar in its elements to that of other extended missions; the minimal operations budget proposal is more comparable to under-guide budgets of other missions.

The panel has some concern about the current maturity of user tools such as the background model and an exposure time calculator. These represent an important component of attracting new users. Given the limited size of the NICER team, the panel recommends that support for the GO program be applied to both support of proposal grants and to other initiatives such as proposal tools and guides, which would aid broader science community involvement in the GO program.

The team should consider the establishment of a NICER Users Group, which could be used for the purpose of developing awareness of NICER and its capabilities, garnering more support within the community, and aiding the NICER team in identifying best practices implemented by other programs. A Users Group could provide significant levels of support and guidance to the NICER team.

The NICER proposal discusses mentoring and career development in terms of how graduate students and early career postdocs have been involved in mission development and are taking advantage of NICER science opportunities.  The panel appreciated that part of the science presentation to the Senior Review was made by an early career scientist.  Further and more detailed consideration of opportunities provided by the NICER mission for scientists at all levels to assume new leadership roles within this mission program, or other mission programs, are strongly encouraged and should be reported in more detail at the next Senior Review.

NICER highlights the capability of doing effective science on ISS. It takes advantage of the ISS accommodations, including the high telemetry rate, that would likely not be available on a dedicated free-flying spacecraft.

**OVERALL ASSESSMENT**

NICER is coming to the end of its prime mission, having been launched less than two years ago. It provides unique capabilities, especially in timing and the soft X-ray sensitivity range,  that complement other missions in the astrophysics portfolio. Improvements in the ToO response will ensure a major role in time domain studies and will take full advantage of the instrument design with its nimble pointing system. We recommend that the team establish a Users Committee to help further develop the user community and to provide prioritized feedback to the team.

The development of the NICER mission has been somewhat limited by the small size of the mission team. The RoM panel supports funding the NICER program at the proposed over-guide level, as it will provide a full GO program and will fund the development of an enhanced ToO response. This budget should be used to provide sufficient resources to further develop community involvement in the NICER mission.

# NuSTAR

## SUMMARY OF MISSION AND PROPOSAL

Launched in 2012, NuSTAR has unprecedented sensitivity in the hard X-ray waveband (3-80 keV) making it the first focusing hard X-ray mission. In addition to high sensitivity, it has high spectral resolution and provides detailed spectra at these energies, is free from pile-up for bright sources, has excellent sky coverage, and can point close to the Sun. NuSTAR began as a PI-led Small Explorer mission and has transitioned to being primarily community-led through a Guest Observer (GO) program, which began in 2015. NuSTAR coordinates observations of targets with many other NASA missions, providing synergistic coverage in hard X-rays, and it has established joint proposal programs with XMM-Newton, Chandra, INTEGRAL, Swift, and NICER. The NuSTAR team proposes to continue operations for the next three years as a community-driven mission, with an expanded GO program and increased responsiveness to target-of-opportunity (ToO) requests, as astronomy moves farther into the time-domain era.

## CRITERION A: SCIENTIFIC MERIT

The scientific return from NuSTAR remains high, with over 500 peer-reviewed papers to date and a publication rate that is still rising, with over 150 papers from the last year alone. It has made exciting discoveries across a range of fields: including probing the conditions of accretion flows onto black holes, constraining the nature of X-ray emitting coronae near accreting black holes, measuring black hole spin, discovering ultra-luminous X-ray pulsars, determining the evolution of supermassive black hole (SMBH) accretion across cosmic time, detecting highly-obscured black hole growth, and characterizing compact objects in the Milky Way and nearby galaxies.

In the last several years substantial progress has been made in understanding the innermost regions of accreting black holes, separating emission from the accretion disk and the compact plasma from the corona, which likely sits above the disk and up-scatters disk photons, as well as identifying coronal emission scattered off the disk. The unique identification of each of these physical regions for individual sources has only been made possible by the unique high spectral sensitivity of NuSTAR at the hardest X-ray energies. NuSTAR has measured temperatures of the corona for individual sources, including finding the coolest known corona to date, and discovering that cooler coronae are in high Eddington ratio sources.

NuSTAR has determined that not all ultraluminous X-ray sources are black holes, finding that at least some of these super-Eddington sources are in fact neutron stars, which was realized when X-ray pulsations were seen from these sources. NuSTAR has made further progress in resolving the cosmic X-ray background and determining the distribution of obscuring column densities around AGN, which is required to construct a full census of SMBH accretion.

Since the last Senior Review the mission has transitioned from being PI-led to community-led, with an increased GO program and the creation of a User's Committee in late 2017. As NuSTAR has transitioned to a more mature mission, the GO program has remained as oversubscribed now as when it started in 2015, and there has been a substantial recent increase in the number of ToO requests from the community. NuSTAR routinely conducts joint observations with other missions, and is clearly an integral part of the larger NASA X-ray mission ecosystem. For example, almost every NuSTAR target is observed by Swift, highlighting the strong synergy between these two missions. Looking to the future, NuSTAR will have notable synergy with the XRISM mission, which will lack a hard-energy camera.

The NuSTAR team proposes to continue transitioning from science team-led legacy programs to community-led large programs, while continuing to lead legacy surveys to follow up Swift-BAT sources. They further propose to emphasize time domain and multi-messenger astronomy in the coming cycle, taking advantage of NuSTAR's full sky coverage and good timing capabilities.

**CRITERION B: RELEVANCE AND RESPONSIVENESS**

NuSTAR is highly relevant to the objectives and focus areas described in the SMD Science Plan, and to the goals of the Astrophysics Division. It addresses key Decadal Survey questions such as, "how do black holes grow and influence their surroundings?", and it addresses NASA Physics of the Cosmos questions related to testing the physics of extreme gravity and the formation and evolution of SMBHs.

NuSTAR was responsive to the 2016 Senior Review report and suggestions, addressing both the programmatic and administrative recommendations of the review by making strong progress against the 2016 Primary Mission Objectives (PMOs). In particular, in the latest GO cycle up to 2 Ms of time have been allocated for new Large programs (>500 ks), and the team has reduced the administrative costs of grants.

**CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS**

The spacecraft, telescope, and detectors are in good health. The mission has continued to function well, with all subsystems being fully operational and meeting or exceeding their design requirements. The projected orbit lifetime exceeds ten years, and the satellite has no consumables. Therefore, extending the mission leverages this potentially long lifespan.

There are minor technical issues related to a decrease in the signal levels from the laser metrology system and degradation in the thermal blanketing. While the cause is unknown, the laser power can be increased to compensate for the diminished signal. These issues are expected to remain minor in the next several years.

The overall budget of ~$8-8.5M per year appears to be reasonable. The under-guide includes a reduction in funding for the Legacy survey data analysis, led by the NuSTAR science team. The over-guide includes support for additional ToO and DDT observations, funding for engineering support of thermal analysis, as well as porting the sky background tool to a new platform and documenting it for use by the broader community. The over-guide proposals were deemed to be of high value by the panel, while at the same time some of this cost may be found by implementing a portion of the under-guide budget. Specifically, the panel recommends that a portion of the budget allocated for the Legacy survey data analysis could be used to implement the over-guide budget. This would include updating and documenting the sky background tool, expanding ToO observations, and performing the proposed thermal analysis.

**OVERALL ASSESSMENT**

NuSTAR is a valuable component of the suite of NASA operating missions. It continues to produce ground-breaking, high-quality science with its unprecedented sensitivity in the hard X-ray waveband and a vibrant GO program. The transition from being a PI-led to GO-led mission has been slower than other extended NASA missions. NuSTAR was very effective in building up the science team early in the mission lifetime, and it should now transition to viewing the team as being part of a broader user base community.

The fraction of DDT time that is utilized for unanticipated ToOs, as well as the process for determining which ToO requests are conducted, is currently not clear. We recommend that NuSTAR explicitly specify what fraction of DDT time will be used for ToOs, while formalizing and making transparent to the community the unanticipated ToO allocation process. We further encourage NuSTAR to develop metrics to assess the success of the new Large programs, to determine whether to expand the allocation for Large programs in the future.

As expanded GO access increased the need to manage and support GO proposals, some of the cost benefits of increased experience leading to higher efficiencies and better economies might still be anticipated. Additionally, we recommend that economies be found within the in-guide budget to support the over-guide request. A significant component of the in-guide budget is support for the Legacy team data analysis. We regard this component as lower priority than implementing the over-guide proposal.

# Swift

## SUMMARY OF MISSION AND PROPOSAL

Swift is a mission designed to locate and characterize transient events, with the initial primary mission goal to study Gamma-Ray Bursts (GRBs). Over time, the mission focus has expanded to include multi-messenger and time domain astronomy. Swift has three instruments: a large field of view Burst Alert Telescope (BAT) covering 15-350 keV; a pointed X-Ray (0.3-10 keV) telescope (XRT); and a pointed UV/Optical telescope (UVOT). The pointed telescopes provide localization of transient sources with accuracies of ~2” (XRT) or 0.5” (UVOT). The observatory can very rapidly slew to respond to a large number of Target of Opportunity (ToO) requests.The Swift team proposes to continue operations with an in-guide budget of ~$5.5M per year. Three over-guide requests for additional funding and one over-guide request for an un-funded science program are proposed to increase mission efficiency and science return and to augment guest investigator funding.

## CRITERION A: SCIENTIFIC MERIT

Swift continues to play a critical role in localization and characterization of transient sources, making it a key asset in the mission portfolio, particularly in the emergent fields of Multi-Messenger and Time-Domain science. It is the only mission in the portfolio capable of extremely rapid multi-wavelength follow up capabilities. Swift is a highly synergistic mission; localization of a transient event often leads to follow-up observations by other missions in the portfolio along with observations from the ground. Swift also provides long term monitoring of UV/Optical and X-Ray for time varying sources, often in concert with other space and ground assets. The recent examples of the neutron star-neutron star merger GW170817 (Swift + Fermi + Chandra), the ultra-high energy neutrino producing blazar TXS0506+056 (Swift + Fermi + NuSTAR), and the new blue transient AT2018cow (Swift + Fermi + NuSTAR + TESS) are all examples of these synergies. Although the mission has expanded far beyond GRB science, Swift continues to provide new discovery in this field both in the high redshift ($z > 6$) and high energy regimes.

The science programs and PMOs identified in the proposal reflect the continuing change in Swift science to further expand the ability to localize and characterize events in the time domain and multi-messenger era, and present a broad and compelling set of science opportunities for the next five years. EM localization and follow-up to LIGO/Virgo events will be a key capability of the mission with an increased cadence over the previous LIGO O2 run. LIGO O3 has begun and has already provided two events that Swift attempted to localize in the first month of operations. Future upgrades to facilities, such as IceCube, will also increase the cadence of Swift multi-messenger science observations. In the coming years, LSST will join the Zwicky Transient Facility in providing far more events than Swift can follow-up, providing both large science opportunity and operational challenges, the latter of which the team is preparing for.

The publication rate of Swift science remains very high, with over 375 papers per year using Swift data in each of the years since the 2016 Senior Review. Publications using Swift data represent a wide range: Swift can be the primary data source, a multi-wavelength partner, or a source for localization that leads to significant detailed follow-up by other facilities. The GI oversubscription rate is very high, indicating a healthy interest in Swift data by the community. The data are delivered extremely rapidly to the community, with initial event information available within minutes and full data within approximately a week.

## CRITERION B: RELEVANCE AND RESPONSIVENESS

Swift directly addresses the 2014 SMD Science Plan in two of three astrophysics imperatives ('Discover how the universe works' and 'Explore how the universe began and evolved'), and is making contributions to addressing the third ('Search for life on planets around other stars') by monitoring low mass stars for UV and X-Ray variability.

Three science PMOs were identified in the 2016 Senior Review proposal: electromagnetic counterparts to GW events, leading the time-domain revolution, and probing the epoch of reionization. Although the event rate is low for the first and third PMOs, Swift has successfully demonstrated science returns in all three.

Swift received over-guide funding for development of large-area tiling capabilities. This capability was successfully implemented (for example, it was utilized for a very recent binary neutron star merger event) and is likely to be an important tool for follow-up of future LIGO/VIRGO events.

## CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

The Swift spacecraft and instruments are healthy, with no serious concerns over the proposed extended mission period. The median time estimate for spacecraft re-entry is 2033. Ground station coverage is provided in-kind by the Italian Space Agency. The total workforce is lean for a very dynamically scheduled telescope. The proposal describes how Swift data are being used to train the community in the science that the mission explores, and it adequately describes how the Swift team itself is training scientists and engineers in operations and management.

The over-guide requests are for: 1) funding to develop an API for ToO submission and scheduling, 2) funding to create an automated UVOT light curve generator, and 3) augmentation of GI funding of $200k/yr.

**OVERALL ASSESSMENT**

Swift remains an essential component of the NASA mission portfolio. The mission is highly responsive to changes in the transient science landscape. The PMOs identified in the proposal are highly relevant and directly address NASA science goals. The Swift team has consistently identified the needs of the community and has adapted to them. The Senior Review encourages the Swift team to seek ways to educate its user base as to when the Swift XRT is the best instrument to employ, and to provide advice as to when a different mission, e.g., NICER, might be a more suitable choice.

Regarding the over-guide requests, the Senior Review strongly supports the API and light curve requests and supports augmentation of GI funding if the NASA Astrophysics budget allows.

# TESS

## SUMMARY OF MISSION AND PROPOSAL

The Transiting Exoplanet Survey Satellite (TESS) is a NASA mission designed to do nearly all-sky photometric monitoring in the red-optical, with a main science case to find thousands of transiting exoplanets around stars in the solar neighborhood. The mission is well on pace to reach its level-1 science requirements: to discover and determine the orbits and masses (via follow-up ground-based radial velocity) of 50 planets smaller than Neptune. TESS proposes for an extended mission that complements its previous observational strategy with observations of new parts of the sky (the ecliptic), a higher cadence of most observations, and community-driven science goals that focus on significant additional planet finding, while also highlighting the benefits of TESS to stellar astrophysics, extragalactic astrophysics, and solar system science.

## CRITERION A: SCIENTIFIC MERIT

The TESS mission is in its early stages, but it is clearly returning excellent quality data that is stimulating a great deal of scientific activity and a wide variety of discoveries. The number of planets found per month is in line with expectations from the Kepler Mission, and the proposal makes clear the significant value of finding these planets in the solar neighborhood, where followup to determine planetary masses, and perform atmospheric characterization, can be performed over the near-term and long-term. A number of small planets with well-determined masses have already been published, with many more papers in preparation.

TESS data are being actively used by the science team and by many in the exoplanet community. Ground-based follow-up efforts, including adaptive optics imaging and radial velocity monitoring, have been well organized and effective. Over half of the Guest Investigator proposals are outside of the field of exoplanets, showing the wide interest in and use of the mission. These have been most numerous in stellar astrophysics, to perform asteroseismic investigations, with a growing component in extragalactic astrophysics.

The expected planetary return for TESS's extended mission is high, pushing well beyond the prime mission. Due to the longer time baseline, together with solid Kepler exoplanet demographic statistics, the team makes a strong case that the extended mission will nearly triple the detection of planets smaller than 4 Earth radii in the extended mission, compared to the prime mission, nearly triple the number of detected planets in the habitable zone, and more than triple the number of planets with periods beyond 20 days.

A major proposed advance in the extended mission is the change from 30-minute full-frame images (FFIs) to 10-minute FFIs. This will allow for accurate planet-finding essentially on any relatively bright star in the FOV, rather than predominantly stars on the 2-minute cadence. This frees up the 2-minute cadence to be fully filled by targets from the GI program, which could include any kind of astrophysical source. Planetary and orbital parameters for planets found from the FFIs will also see a significant increase in signal-to-noise. The 10-minute FFI cadence will have a large impact on asteroseismology by enabling detections in stars with shorter characteristic oscillation frequencies. It will also greatly expand the opportunities for serendipitous time-domain discoveries.

The capability to carry out 20-second cadence observations for selected targets is an interesting new opportunity, the return of which is harder to predict but could be significant.

The extended mission plan is well designed and allocates the great majority of short-cadence target observations to community proposals. In terms of fields, the extended mission will observe most of the area of the sky missed during the prime mission, improving the archival legacy of TESS and greatly improving coverage of the ecliptic.

The MAST archive has done an outstanding job at making data products, and tools to request and analyze data products, accessible to the scientific community.

The synergies of the TESS mission with citizen science and amateur astronomy communities are strong and help to increase the scientific return from the mission and engage the worldwide community.

The non-exoplanet science cases on stellar astrophysics, via asteroseismology across most of the Hertzsprung-Russell diagram, and on extragalactic time-domain transient science, such as pre-discovery time series of supernovae and tidal disruption events and monitoring of active galactic nuclei, are clear and compelling.

Conversely, the asteroid and near-Earth object (NEO) science cases are not as well developed or well described, in particular for NEOs. For asteroid rotational light curves, although the number of light curves will be large, the 10-minute FFI will bias detections toward rotators with periods longer than ~30 minutes, and the proposal did not put these observations in the context of current work from other space missions or from the ground. For NEOs, the proposal failed to establish that the data returned would be of sufficient quality or cadence to be useful to NEO discovery or tracking. The lack of TESS astrometric accuracy, along with the long exposure severely limits its capability in these areas. The proposal lacked enough detail to validate the claimed number of discoveries.

## CRITERION B: RELEVANCE AND RESPONSIVENESS

TESS is directly relevant to the NASA goal to "Discover and study planets around other stars, and explore whether they could harbor life," from the 2014 Science Plan. TESS is the world's main exoplanet discovery instrument and is finding Earth-sized planet targets for atmospheric characterization by James Webb and future space telescopes. It is also generating a wealth of time-domain astrophysics, including stellar asteroseismology and transient astrophysics.

Because TESS did not participate in the 2016 Senior Review, criteria B-2 and B-3 are not relevant. TESS results are just beginning to appear in publications, and all indications are that the data are high quality and that the prime mission is on track to achieve its priority objectives, potentially ahead of schedule.

## CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

The spacecraft health is in some ways even better than expected, like a better-than-new mission. Most importantly, the data download rate is higher than the nominal plan, allowing for the proposed higher cadence of FFI data in the extended mission.

The transition to an even more "open" mission, with important 2-minute cadence targets moved from 80% science team targets to 80% GI targets (0% science team), completes the TESS idea of a community-driven mission.

The role of early career scientists in leading TESS science results is impressive. We commend the team for providing leadership opportunities for early career scientists across a range of mission activities, and we encourage the team to continue to identify such opportunities in the future.

We recommend that the mission examine opportunities for cost savings in the future to ensure a strong evaluation in the next Senior Review. In an extended mission there is an expectation of increased efficiency in performing science operations and science data analysis tasks.

The case for the over-guide budget is strong. Funding the GI program is well-motivated, as ground-based follow up observations are a key to delivering the expected science return of the mission. The small additional cost for the lease on the Attitude Control System simulation software is wise, given the potential for a long lifetime of the mission.

**OVERALL ASSESSMENT**

Although it is still early in the TESS prime mission, the team and proposal make a convincing case that the mission is well on its way to achieving the science goals of its prime mission. They furthermore make an impressively compelling case that the science return of an extended mission would be even greater than that of the prime mission. TESS is an exemplar of a NASA mission that is thoughtfully planning for a future in which the science is community-driven, rather than science-team driven. The innovations of observing cadence (3x higher cadence FFIs, the new 20-sec observing mode) and observing strategy (new areas like the ecliptic plane, the GI program driving the 2-minute cadence program) are designed to increase the community science yields beyond the prime mission.

# XMM-Newton

## SUMMARY OF MISSION AND PROPOSAL

XMM-Newton is a Great-Observatory class X-ray mission that covers the 200 eV to 12 keV band with a broad array of capabilities in imaging, a good point spread function (surpassed in the X-ray only by Chandra) with wide field of view, spectroscopy at both CCD-quality resolution and higher resolution in the 200 eV to 2 keV band, and with options for both rapid timing and long uninterrupted observations. XMM-Newton additionally has simultaneous optical/UV capabilities via its optical monitor. Launched in 1999, it continues to be operated by the European Space Agency. NASA participates in the mission by supporting a Guest Observer Facility at NASA Goddard Space Flight Center, supporting the US component of the Reflection Grating Spectrometer Team, and by funding US-based principal investigators in a guest observer program.

The proposal requests continued funding of the Guest Observer Facility, the US Reflection Grating Spectrometer team (at less than $1M per year for those combined efforts), and US PI investigators (at approximately $2.5M per year). The proposal also requests an enhancement of the guest observer program (an additional $1M per year) to broaden the base of US investigators that could be supported.

## CRITERION A: SCIENTIFIC MERIT

XMM-Newton is a mature mission, approaching 20 years of operations, yet remains one of the premiere X-ray observatory facilities due to its unique combination of capabilities. With excellent soft X-ray response, good point spread function, and wide field of view, XMM-Newton maintains a pivotal role in providing soft X-ray observations to the community. The scientific merit of XMM-Newton remains strong. XMM-Newton offers flexible Target of Opportunity and long programs, which have enabled multi-wavelength science and the creation of legacy data sets. XMM-Newton allows proposals for very large programs (VLPs) with requests for 1–3 Ms of time, and the mission has increased the fraction of time dedicated to large programs (LPs) and VLPs to about 30% of the total observations. This includes a recently implemented multi-year Heritage Program. Proposals as a whole have been oversubscribed by more than a factor of 5, with the Heritage Program having an oversubscription factor of more than 9.

The rate of publications associated with XMM-Newton observations remains high at roughly 250 papers per year, for the past five years. This is comparable to the rate for other major missions. The quality of the papers is high; 37% of XMM-Newton papers published in the last year belong to the top 10% of the most cited articles published in the same time span.

US participation in the program is strong: one third of successful XMM-Newton proposals have US principal investigators, and 70% of all successful proposals have US co-investigators. Synergies with other NASA facilities are also very strong. XMM-Newton is complementary to Chandra (providing wider field of view, higher effective area, and better soft X-ray response), and NuSTAR (providing well-matched effective area and spectral resolution at soft X-rays). XMM-Newton, via cooperative agreements, provides coordinated observations with each of these facilities. It is the only X-ray mission that can perform a continuous >1 day observation with simultaneous optical/UV coverage.

The breadth of science covered by XMM-Newton is very wide. The proposal highlighted significant contributions made with XMM-Newton observations to deep surveys of the X-ray sky, X-ray clusters, SN remnants, Tidal Disruption Events (TDEs), Ultra Luminous X-ray (ULX) sources, stellar astrophysics, and planets. Highlighted analyses of XMM-Newton observations in these diverse areas employed a very wide range of techniques; spatial/spectral analyses have been applied to observations of clusters and supernova remnants, spectral/timing analyses have been applied to TDEs, and high resolution spectroscopy has been applied to the study of outflows in ULXs. The expansive diversity of science and observational abilities achievable by XMM-Newton has led to a broad user and science base for the mission.

## CRITERION B: RELEVANCE AND RESPONSIVENESS

As indicated by the broad array of science topics covered by XMM-Newton observations, it continues to remain highly relevant to NASA priorities, and it is responsive to the NASA goals for astrophysics as described in the 2014 Science Mission Directorate (SMD) plan. As pointed out in their report to the Senior Review, XMM-Newton helps to “probe the origin and destiny of our universe, including the nature of black holes, dark energy, dark matter and gravity”, as well as “explore the origin and evolution of the galaxies, stars and planets that make up our Universe.”

The two Prioritized Mission Objectives (PMOs) set out in the XMM-Newton proposal to the 2016 Senior Review have been achieved. The first PMO was to maintain consistent and effective dissemination of data, software, and analysis guides for US based users to make productive use of XMM-Newton data. The second was to maintain (and expand from $2M to $2.5M funding) a grants program so that US observers would have the resources to extract the best science from XMM-Newton observations. The PMOs described to the 2019 Senior Review continue to build off of the 2016 priorities, with modest and reasonable enhancements.

## CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

The European Space Agency is fully responsible for the operational costs of XMM-Newton, whereas the US funding predominantly provides direct support to the US scientists who are principal investigators on approximately 1/3 of XMM-Newton proposals. The NASA investment in XMM-Newton is thus highly leveraged and is a very cost effective investment for the science returned.

This direct investment in science investigations with XMM-Newton is providing training and experience across a broad range of science areas for graduate students and other young investigators. 75% of guest observer grants support graduate students and/or postdocs.

Overall, the technical and operational capability of XMM-Newton is almost as high as it was in the early years of the mission. Despite its age, the satellite and its instruments are in good health, and no core scientific capabilities have been compromised. XMM-Newton also has had continued improvements in terms of observation flexibility, software, and calibration.

The only major new instrumental development since the last Senior Review is the appearance of a low sensitivity depletion patch in the Optical Monitor, due to an accidental observation of Jupiter in mid-2017. This depletion level is stable, and these pixels are now flagged during data processing. Other than this issue, there are no other issues of concern with the optical monitor.

## OVERALL ASSESSMENT

XMM-Newton has continued to produce Great Observatory scope science at a very modest cost to NASA. US participation in XMM-Newton remains high, and the breadth and impact of the science have continued to be expansive and strong. XMM-Newton is still heavily oversubscribed and being widely used by young scientists.

The Senior Review believes that the overguide request to increase the level of funding for improved support of US-based guest observers would further broaden the US user base for XMM-Newton observations with only a modest additional investment by NASA. The Senior Review suggests that the XMM-Newton Guest Observer Facility survey its user base, going back multiple GO cycles, to solicit feedback over how best to utilize guest observer funds, regardless of whether these funds are augmented as a result of the Senior Review. The principal question is whether to continue the current practice of funding only US PI proposals with A/B grades or to broaden the funding to include either US Co-Is on foreign proposals or US PIs on category C proposals (or both); funding a broader set of selected proposals would necessarily reduce the amount of funding allocated to each individual grant.

In an era where both time domain astronomy and multi-messenger astronomy are becoming increasingly important, with several missions (XMM-Newton, Swift, NICER) playing complementary, although broadly similar, roles in providing soft X-ray coverage for NASA science priorities, the RoM panel encourages the XMM-Newton GOF to seek ways to educate its user base as to when XMM-Newton is the best instrument to employ in such studies, and to provide advice as to when a different mission, e.g., NICER, might be a more suitable choice. The panel recognizes that each of these missions has unique capabilities and wishes to encourage discussion among these mission teams as how to maximize science output from the mission portfolio viewed as a whole.

# 2019 Astrophysics Senior Review

## Hubble Report

# 2019 Astrophysics Senior Review - Hubble Report

**May 6-8, 2019**

**PANEL:**

Roberta Humphreys, University of Minnesota - co-chair
Alexandra Pope, UMass Amherst - co-chair
Lee Armus, Caltech
Hilton Lewis, Keck Observatory
Pamela Marcum, NASA Ames Research Center
Bob Milkey, AAS (retired)
Margaret Turnbull, SETI Institute
Charles ("Chick") E. Woodward, University of Minnesota

## EXECUTIVE SUMMARY

Hubble continues to excel in scientific productivity and remains a key element in the achievement of NASA's strategic goals, and is continuing to meet the aspirations of the worldwide astronomy community. Hubble has clearly demonstrated the United States' leadership in space astrophysics and utilization of advanced space technologies.

Hubble is well aligned with the research objectives of SMD and the scientific goals of the Astrophysics Division. High publication and citation rates attest to the fact that Hubble data, thanks in large part to the level of observatory and instrument support provided by the Space Telescope Science Institute, is extremely valuable for answering the key science questions driving astrophysics today. Hubble enables a truly astonishing range of science and the Project continues to be responsive to the changing scientific landscape. The dual-anonymous reviews as a prime example of the Project's forward-thinking leadership status in the astronomy and broader scientific community.

The Project has made very good progress against the 2016 scientific and technical primary mission objectives. In particular, the Hubble Source Catalog (HSC), the Hubble Spectroscopic Legacy Archive (HSLA) and the creation of full depth mosaics facilitate a variety of new science that would be extremely difficult to reproduce by individual investigator teams.

The Project has taken a proactive stance on mitigating the likely failure modes and degradation in the telescope and instrumentation. This planning is crucial for maximizing the cumulative scientific impact of the observatory. The Project has put substantial effort into assessing, analyzing and preparing for future failure modes, including preparation for operations with the expectation that one or more gyros fail by 2025.

While the scientific impact of Hubble is indisputable, the report contains insufficient information to fully assess the allocation of resources. The Panel also had some concern with the migration and distribution of data analysis software, GO funding levels and the long-term support for archive access. Recommendations made in this report to address these concerns are motivated by a desire for the Project's high productivity to continue even as the Project undergoes inevitable near-term transitions including entering a JWST era, gyro failures, etc.

Hubble is a clear international leader in science, stewardship and operations. Hubble's value goes beyond the criteria we were asked to evaluate. For example, the public outreach program is a model for other observatories - the impact and value of these efforts on the public's appreciation of astronomy and science in general are invaluable.

ADJECTIVAL RATING FOR SCIENCE MERIT: **EXCELLENT**
ADJECTIVAL RATING FOR RELEVANCE AND RESPONSIVENESS: **EXCELLENT/VERY GOOD**
ADJECTIVAL RATING FOR TECHNICAL CAPABILITY AND COST REASONABLENESS: **EXCELLENT/VERY GOOD**

OVERALL ADJECTIVAL RATING: **EXCELLENT/VERY GOOD**

## CRITERION A: SCIENTIFIC MERIT

**The Hubble Senior Review Panel finds that the scientific merit of the Hubble mission remains excellent.**

As the first of NASA's Great Observatories, the Hubble Space Telescope has clearly demonstrated the United States' leadership in space-based astrophysics and advanced space technologies, inspiring the global public to contemplate and engage with the cosmos in a scientific way. At nearly 30 years of age, the Hubble Space Telescope is still at peak performance in terms of efficiency and instrument performance and calibration, enabling a diverse community of users to open new discovery space via both new observations and archival data-mining activities. Assuming the mission continues to age gracefully, the Hubble Space Telescope will continue to be a critical component of NASA's Astrophysics portfolio deep into the next decade, serving as a complementary element to many NASA Planetary Missions and future astrophysics missions such as the James Webb Space Telescope.

Hubble's ability to conduct observations in the ultra-violet (UV) is an especially important complement to observations in other spectral ranges. The Hubble Space Telescope's unique capabilities in this area are unlikely to be equaled for decades to come. Given the limited lifetime of the mission, the Hubble Senior Review Panel urges the Hubble Project to continue supporting large community-motivated efforts (akin to Frontier Fields and ULLYSES) with a special focus toward Hubble's unique capabilities (UV and otherwise) that are unlikely to be reproduced in the near future. The Hubble Senior Review Panel recommends that the Project should create a "bucket list" for the mission, asking: "What ambitious undertakings could be carried out during Hubble's remaining years that we would regret not doing?"

Hubble remains a facility that supports a cross-disciplinary, international community with wide-ranging scientific goals and objectives, and boasts the most extensive scientific publication record of any astrophysical initiative. Synergistic use of the telescope to complement other NASA missions continues to be of great value and contributes significant benefit and return on investment. The cross-mission support is advancing progress in Decadal Survey science goals to which many NASA SMD Science Plan Objectives are closely aligned.

Archival use of Hubble data for context and discovery purposes continues to grow as new science areas open, such as Multi-Messenger Astrophysics and distant solar system small body reconnaissance. The Hubble Project continues to innovate by providing the community with a robust archival capability, including "on-demand" data processing with the most recent pipeline and associated reference files for investigators. The provision of such tools enhances usability of the extensive assets in the Hubble archive. Several updates to the data analysis and archiving described in 2016 PMO 5/6/7 and 2019 PMO S2 will foster an enduring high science yield from the archive during the current mission phase and beyond as a lasting legacy. Specifically, the improved Mikulski Archive for Space Telescopes (MAST) portal, adding the Hubble Spectroscopic Legacy Archive to the MAST, and expansion of super mosaic capabilities to proprietary datasets will enable new, value-added science (2019 PMO S2). Proposed science-driven portals for other disciplines, including the deep-field portal currently in development, are of special interest and should have a clearly defined delivery schedule. The MAST Archive is perhaps Hubble's greatest contribution to astronomy, and the Project should have a plan for its continued support long after the mission ends.

Multi-messenger astronomy affords the opportunity to make significant advances in astrophysics. Rapid response to trigger events will be necessary to maximize the scientific potential of this new mode of observing. Moreover, Hubble will play a key role in enabling science from the ensemble of space and ground assets. The Project should consider whether the current processes, scheduling, and observing modes fully support the exciting science opportunity at hand.

Time Domain Astronomy, including exoplanets transits and phenomena revealed by projects like Zwicky Transient Factory [ZTF] and in future the Large Synoptic Survey Telescope [LSST], are an increasing part of the astronomy landscape. Hubble has the potential for significant contributions in this area of exploration. However, capitalizing on these opportunities represents a significant demand on scheduling, which must be accommodated within current resources. The Project should engage in meaningful dialogue with the Space Telescope Users Committee (STUC) and the broader community to ensure an alignment on Time Domain Astronomy (TDA) observing priorities.

Education and public outreach are two of the Hubble Project's greatest legacies, magnifying the return on investment in incalculable ways. Hubble's stunning imagery of the universe has captivated and engaged a global audience through informal and K-12 educational channels, and its critical capability has motivated hundreds of doctoral theses advancing the entire fields of planetary and astrophysical science. The Mission has likewise provided a leading gateway for workforce development, driven by innovation in engineering, system operations, project management, and complex data analysis algorithmic development that deeply penetrates many areas of NASA strategic concern. The Hubble Space Telescope is forever embedded within the fabric of human achievements, the fruits of which legacy will continue to unfold for generations to come.

To summarize, the Hubble Senior Review Panel finds that the scientific merit of the Hubble mission remains excellent, with several specific recommendations for consideration in the coming years:

- The MAST Archive, as one of Hubble's greatest legacies, should have a clear plan for support long after the end of the mission itself, including remaining freely available to the global public.
- The Hubble Project should have clear delivery timelines for science-driven specialty archives (e.g., the proposed deep-field portal) and inter-archive tools.

- The Hubble Project should consider the creation of a special archive for delivering theoretical results based on HST observations and archival studies (e.g., simulations and models).
- The Hubble Project should continue to proactively engage with the scientific community in crafting a “bucket list” of uniquely HST-enabled observing programs (e.g., UV observations) that could be prioritized for the facility’s remaining lifetime.
- The Hubble Project should explore strategies for supporting observing modes that are critical to time-domain and multi-messenger astrophysics.
- The Hubble Project should consider whether the current processes, scheduling and observing modes fully support the exciting science opportunity afforded by Time Domain Astronomy in all areas of astrophysics and planetary science.

The Hubble Senior Review Panel’s assessment that the Hubble Space Telescope return continues to yield significant value to NASA SMD mission portfolio and the national enterprise of leadership in discovery science, in part was driven by recent accomplishments – highlights of which are described below.

**Diversity of exoplanet atmospheres and their host stars.**

*Major Findings 2016 to Present:* We now know that exoplanets are ubiquitous, orbiting around most stars in our galaxy. The science paradigm has changed from one of discoveries to that of understanding the demographics of these populations. Hubble is a pre-eminent space observatory for characterization of exoplanet atmosphere using spectroscopic techniques using the transiting techniques, establishing foundations for establishing metrics to test for habitability using atmospheric biomarkers as we search for life elsewhere.

*Status:* In progress. Hubble’s access to wavelength ranges from far-ultraviolet to near-infrared are now routinely used to conduct reconnaissance of the chemical composition of exoplanet atmospheres, including detailed understanding of cloud/haze formation and atmospheric mass loss. Comprehensive datasets of hot-Jupiters are being assembled to probe the water content and presence of alkali species in these objects, providing links to understand the formation and evolution of these planets. Investigation of the Earth-sized exoplanets in the TRAPPIST-1 system offer insight into the evolution of Earth’s atmosphere, from a hydrogen-helium primordial atmosphere to a secondary atmosphere with water, carbon dioxide and/or methane. These spectral libraries are of high value and provide synergy for future NASA Astrophysics mission, including JWST.

*Notable Reference(s):* Tsiaras et al. 2018, AJ 155, 156; Wakeford et al. 2018, AJ 155, 29; Line et al. 2016, AJ 152, 203

**Dynamical and chemical evolution of outer planets and satellites.**

*Major Findings 2016 to Present:* Use of Hubble has been pivotal to investigating interstellar visitors to the Solar System (the 'Oumuamua event), studying the water plumes on Europa, providing critical navigation observations of Pluto and the multiple moons of this dwarf planet for the NASA New Horizons flyby, while continuing legacy observations for the outer planet atmosphere programs producing global planetary maps. All are pivotal to scientific objectives of ascertaining the content, origin, and evolution of the Solar System, and the potential for life elsewhere.

*Status:* In progress. The Hubble OPAL (Outer Planets Atmosphere Legacy) program is continuing, in part complementing observations by the NASA Juno mission. Further studies of Europa's water plumes are ongoing, providing context for future in-situ NASA mission measurements focused on assessment of life-potential, while asteroid and comet studies advance.

*Notable Reference(s):* Mecheli et al. 2018, Nature 599, 223; Lauer et al. 2018, Icarus 301, 155; Sparks et al. 2016, ApJ 829, 121

**Measuring Hubble Constant ($H_0$) to 1% Precision and the Advent of New Physics**

*Major Findings 2016 to Present:* Hubble has played a critical role in the era of precision cosmology through the use of specific cosmological markers, including Type Ia supernovae, strongly lensed quasars, and standard candles including Cepheids at the tip of the red giant branch. Emerging out of these efforts is a "Hubble tension," wherein a significant (of order 9%) discrepancy has emerged between measures of the $H_0$ directly from Hubble data and that deduced from studies of the cosmic microwave background (CMB). This dissonance may suggest that new fundamental physics discovery space is opening, potentially including exotic dark energy, or dark matter-radiation interactions.

*Status:* In progress. New approaches combining Hubble measurements of Cepheids in nearby galaxies that host Type 1a supernovae with GAIA recalibration of the Milky Way Cepheid Period-Luminosity function (to of order 0.4%) to achieve the desired 1% measurement of the Hubble constant, and thereby constrain whether the Hubble tension is caused by systematic errors. Further observations of multiply imaged lensed systems will provide an independent 1% measurement goal. Follow-up observations of supernova 1a at $z > 1$ will be necessary to assess whether the dark-energy equation of state varies over cosmic time.

*Notable Reference(s):* Riess et al. 2018, ApJ 861, 126; Sharon et al. 2017, ApJ 835, 5; Casertano et al. 2016, ApJ 825, 11

**Exploration of the Distant Universe**

*Major Findings 2016 to Present:* Hubble has provided the deepest images of the distant Universe ever obtained with the completion of the Hubble Frontier Fields (HFF) program (over 840 dedicated orbits), which produced images of several hundred galaxies extending back to the epoch of reionization at $z > 6$. New insights regarding the formation of galaxies is emerging.

*Status:* In progress. Hubble observations, complemented by Planck observations of the Cosmic Microwave Background, indicate that reionization was rapid. Galaxies likely are the dominant source of the ionizing photons of the intergalactic medium, provided approximately 20% of their ionizing photons escape. At distant times ($z \sim 9$), the intergalactic medium was primarily a neutral phase, and was almost completely ionized by $z \sim 6$. The HFF lies at the foundation of many follow-on initiatives, including those with ALMA, the Very Large Array, JWST, and focused Hubble studies of peculiar lensed clusters. The stunning imagery has also captured the public imagination.

*Notable Reference(s):* Ishigaki et al. 2018, ApJ 854, 73; Lotz et al. 2017, ApJ 837, 97; Livermore et al. 2017, ApJ 835, 113

**Legacy Utilization of the Hubble Data Archives**

*Major Findings 2016 to Present:* The extensive archives obtained over several decades are providing critical data to enable new science and exciting unanticipated phenomena in time domain astronomy. Discovery of transients in multiple exposure visits to Frontier Fields has created opportunities to conduct precise cosmological tests of gravitational lensing physics, deeply probing our understanding of Einstein's theory of General Relativity.

*Status:* In progress. Predictions of time-delayed appearance of the same supernova in a lensed system have been confirmed. Direct imagery of strongly lensed super star clusters (magnifications upwards of 70 times) at cosmological distances ($z \sim 6$) have enabled spatial studies reaching 13 pc effective radius. The contribution of primordial black holes to the distribution of dark matter is under investigation.

*Notable Reference(s):* Windhorst et al. 2018, ApJS 234, 41; Kelly et al. 2018, Nature Astronomy 2, 234; Vanzella et al. 2017, ApJ 842, 47

**Exploiting the Ultraviolet Niche**

*Major Findings 2016 to Present:* Hubble has unique capabilities to probe physical phenomena in the ultraviolet (UV) region of the electromagnetic spectrum where atomic and ionic transitions provide a rich set of diagnostics for determining temperature, density, elemental abundances, accretion rates, and mass loss in a variety of astrophysical environments. Growing exploitation of the UV is commencing with the UV Initiative, which has the objective of generating legacy treasury data sets in key thematic areas, in anticipation of a several decade hiatus in observational capability at these wavelengths upon loss of Hubble.

*Status:* In progress. Auroral morphology in Jupiter's polar regions are providing synergistic context for detailed *in situ* investigation conducted by the NASA Juno mission. Comprehensive investigation into the formation and evolution of spatially resolved young stellar clusters (YSC) in nearby galaxies has revealed hierarchical structure of these star-formation regions. Commencement of the multi-cycle UV Legacy Library of Young Stars as Essential Standards (ULLYSES) is forthcoming, a community driven initiative to assemble UV spectroscopic template sample of young high- and low-mass stars.

*Notable Reference(s):* Grodent et al. 2018, JGRA, 123, 3299; Adamo et al. 2017, ApJ 841, 131; Roederer et al. 2018, ApJ 860, 125

<u>ADJECTIVAL RATING FOR SCIENCE MERIT</u>: **EXCELLENT**

**CRITERION B: RELEVANCE AND RESPONSIVENESS**

**Factor B-1: Relevance to the research objectives and focus areas described in the SMD Science Plan. Relevance to the scientific goals of the Astrophysics Division as defined in the Division's Strategic Objectives and the 2010 Astrophysics Decadal Survey.**

Through the combination of Legacy type programs, DDT initiatives, expanded multi-mission support, and a wide variety of small, medium and Large GO programs, Hubble continues to be well aligned with the research objectives of SMD and the scientific goals of the Astrophysics Division. High publication and citation rates attest to the fact that Hubble data, thanks in large part to the level of observatory and instrument support provided by the Institute, is extremely valuable for answering the key science questions driving astrophysics today. It is clear to the Panel that Hubble enables a truly astonishing range of science, and that the Project continues to be responsive to the changing scientific landscape.

The seven 2019 PMO's presented by the Project, in part, are directly traceable to objectives in SMD science plans and themes discussed in the 2010 Astrophysics Decadal Survey. The 2019 PMOs were developed with input from and review by the Space Telescope Users Committee (STUC) and are defined in into two categories, programmatic and scientific. The Panel's consensus is that such division is appropriate for the HST observatory for which the science is community driven. The 2019 programmatic PMO's encompass the goals of keeping Hubble operating for maximum science while seeking operating efficiencies to reduce costs. The 2019 scientific PMO's recognize the need to select and support the community-driven science both through new observations and improved archive access, HST's unique capabilities for UV observations, and the changing requirements that will result from the successful operation of JWST.

**Factor B-2: Progress made toward achieving Prioritized Mission Objectives (PMOs) in the 2016 Senior Review proposal**

The mission has made very good progress against most of the scientific and technical PMOs described in the 2016 Senior Review proposal. These studies range from tracking Solar System storms, to measuring exoplanet atmospheres, to inferring the properties of $z > 10$ galaxies. Science is being done now with Hubble that was not even considered at launch. The same is true for the more technical 2016 PMOs that relate to the archive, HLA and new data queries. Ongoing and planned efforts to create wider catalogs, and better mosaics will greatly benefit the community. In particular, the Hubble Source Catalog (HSC), the Hubble Spectroscopic Legacy Archive (HSLA) and the creation of full depth mosaics (2016 PMOs 5, 6, and 7) have already begun, and should continue to enable, a great variety of new science that would be extremely difficult to reproduce by individual investigator teams.

One of the 2016 PMOs (#8) was the enabling of new cross-archive queries and capabilities. This activity is also carried forward with 2019 PMO S2. The first product of this PMO for exoplanets is the exo.MAST effort, which is impressive and well received by the Panel. In the report, there was little discussion of what the plan was for additional efforts along these lines, other than a mention that a future science area would be in extragalactic deep fields. A more detailed written plan for these additional capabilities would have been helpful. A more thorough description was provided verbally during the follow-up discussion at the review, and the Panel looks forward to the implementation of these initiatives.

**Factor B-3: Performance of addressing any findings in the 2016 Senior Review**

The following are a list of the recommendations from 2016 Senior Review :

*1. Responsiveness and advance information* – The Project provided a timely written response to questions submitted in advance by the panel members.

*2. Report progress against PMOs* – The 2019 Senior Review proposal provides a comprehensive overview of the progress against most of the PMOs outlined in the 2016 proposal as described above in answer to criterion B-2. In a related request, the 2016 Senior Review Panel indicated that "The HST community should be explicitly consulted in developing community enabling PMOs . . . and the final choices should be reviewed by representatives of the community." The choice was made to use the Space Telescope Users Committee (STUC) for this purpose and this seems to be a reasonable approach. We also encourage STScI management to continue to actively seek alternative sources of input for future science initiatives outside of the STUC, in order to reach a wider portion of the community.

*3. Convene a task force to examine the impact of inflation on GOs* – This recommendation was addressed by the Project by preserving the budget profile. The GO/AR budget remains relatively flat (in-guide budget) and it is stated that the supported level of postdoc and graduate student personnel has remained essentially steady for several years. How the Project will accommodate long-term inflation within the flat funding levels remains unclear.

*4. Resource Allocation* – STScI asserts a bottom-up evaluation was performed, but only provided minimal information about how this analysis was conducted. With this level of information the Panel was unable to fully evaluate the adequacy of the budget in meeting the budget pressures and anticipated technical challenges in the years ahead.

*5. Science Enhancements* – The Project provided a substantial amount of information detailing the various initiatives undertaken to enhance the scientific capabilities of HST in response to the comments from the 2016 Senior Review Panel.

6. *Replacement of IRAF with updated tools for data reduction and analysis* – In 2016, the Project recognized antiquated software as a problem and has since been working on upgrades. Software used for internal processes was updated first, and is now being extended to the tools

being used by the community. Moderate progress has been made to address the stewardship of reliable, integrated data reduction and analysis software packages that are well vetted. IRAF is not running on virtual machines; only partial migration of image-related algorithms to the Python environment has occurred, while support for spectroscopic modes within interactive GUI environments is not mature. Outsourcing the responsibility to the community to develop these tools may not be a prudent strategy as the timeliness of deliverables is compromised by unpredictable interest, effort, and lack of funding resources. These tasks have relied largely on volunteer efforts of less senior members in the profession (e.g., the Astropy group, and affiliated Python package developers). Science return from Hubble, JWST, and future astrophysics missions may be negatively impacted without development of such infrastructure.

Maximizing return from Hubble data requires a data reduction environment that is stable, vetted, and curated effectively to ensure the legitimacy of data products that are used for science interpretation and enable processes to reproduce these data by independent groups of investigators.

ADJECTIVAL RATING FOR RELEVANCE AND RESPONSIVENESS: **EXCELLENT/VERY GOOD**

## CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

### Factor C-1: Cost efficiency of the mission's operating model in terms of meeting the proposed scientific goals, and current operating cost

The Project is to be commended for its continued innovative efforts in finding operational efficiencies that both enhance science productivity and quality as well as provide cost savings that can be reallocated to benefit other areas of the Program. Examples of recent efficiencies, the cost savings which have helped offset the effects of inflation within the constraints of a flat budget, include: cross-training JWST staff to obtain Hubble expertise, consolidating database ground-systems, eliminating the support of multiple, redundant calibration pipelines at multiple institutions. On the topic of observing efficiency (specifically, the percentage of a complete orbit spent collecting data while pointed at a target), the Project indicates that this efficiency has plateaued at ~58% (a limitation set by the near earth orbit parameters) and likely no further cost savings can be realized within the current "Great Observatory" operations model, a model that the Project intends to continue following through the horizon of the timeline covered by the Senior Review.

While the Panel regards the in-guide budget as sufficient for Hubble science to continue at the same high level of performance for the next three years in the absence of any unexpected or unmitigatable crises, the proposal and subsequent discussion with the Project leadership did not provide sufficient information to demonstrate that the observatory was, in the words of the narrative itself, operating on a "lean" budget. *Cost* efficiency (e.g., science per dollar) could not be properly evaluated, nor was a thorough evaluation on this topic possible during the limited time of the Senior Review. While the proposal states that "a bottoms-up review" has been conducted, important details such as the findings of the review were omitted from both the proposal as well as from written and verbal communication with the Project. This critical information, had it been included in the proposal's narrative, could have been used as a robust justification for the Project's proposed budget profile and perhaps alleviated the majority of the above concerns of the Panel.

### Factor C-2: Health of the spacecraft and instruments, and suitability of the mission's operating model (e.g., governance, science team, instrument team) to maximizing its scientific return

The Panel commends the Project for its proactive stance in mitigating likely failure modes of the telescope and instrumentation through careful analysis and advance preparations. This approach is crucial for maximizing the cumulative scientific impact of the observatory across its full lifetime. Further, the vetting of priorities for these activities with the STUC is a sign of a healthy interaction with the community. Two noteworthy examples are: (1) the preparation for Hubble's future operations with the prospective failure of one or more gyros by 2025; and (2) dealing with current issues through instrument innovations like COS2025, extending the science productivity of the instrument years into the future. The Panel found these efforts to be appropriate, timely and a strong indicator of a well thought-out approach to maintaining long-term capabilities.

The Project should give thought to the prioritization of resources to address the possibility of multiple or unanticipated failures. Such a list will likely need to be adjusted after JWST is launched and its actual operating characteristics are better understood. It is probable that the maintenance of observational redundancies with JWST will be deprioritized at this stage.

Mission success has been critically dependent on the skill, creativity and dedication of current project staff, and the continuation of this capability will be fundamental to the Project's ability to deliver in the more challenging years ahead. There was little discussion of critical issues around identification of key skills, single points of failure, succession planning, or dealing with the likely brain drain to JWST. We note that the Project has documented several activities completed and in progress to extend the life of the Hubble. The Panel urges the Project to continue to develop a clear plan and to assign the appropriate level of resources to mitigating future risks.

**Factor C-3: In the context of the expected lifetime of the mission, the Project's plans to prepare for the future by providing the training, mentoring and leadership opportunities that will expand the skills of its staff, as well as foster the next generation of mission leaders**

The Project has a strong and illustrious history of developing and mentoring its human talent, both early and mid-career staff, evidenced by the number of successful leaders within the global astronomical community who began their careers at Hubble/STScI. Details of the continuation of these mentoring programs were not discussed in the proposal, though they were well described in subsequent face-to-face discussion with the Project team. The Panel strongly endorses the continuation of these practices, as is consistent with the role of HST as a Great Observatory.

One minor suggestion offered by the Panel is to consider a broader professional management training experience for early-career staff members that goes beyond internal mentorship and training programs and that would prepare participants for leadership positions that are applicable to career pathways beyond HST and JWST. Such a program could include project management best practices, including topics such as risk management and conducting science/budget tradespace studies, mission risk analysis.

**Factor C-4: Current operating costs**

The Panel considers the proposed budget, which keeps the operating costs equivalent to the same level as previous cycles, to be sufficient to maintain the current science productivity as well as to make preparations for the eventual demise of some subsystems. The Panel does not identify any mission critical tasks that are unmanageable within the current in-guide budgetary envelope. The Panel believes that the Hubble Space Telescope operational efficiencies and science return at the in-guide levels of investment are robust and sufficient to carry the Hubble Project over the period of FY20 through FY22.

The in-guide budget shows an average increase of about $2.7M to the Guest Observer budget line over the next 5 years. This increase, a request that was called out in the 2016 Senior Review findings, is made possible by the offsetting decreases broadly applied to other areas of the budget. One such area is mission operations at NASA GSFC, which has been transformed from a continuous to a 5 day / 7 hour operations schedule. This downsizing assumes a risk posture whose basis is on past performance at a time when the spacecraft and subsystems were working at peak performance and not nearing end-of-life. The mission operations staffing profile has a downward trend in the proposed in-guide budget, a concern to the Panel given that the mission is likely to be shifting into the complexity of reduced gyro mode within the next few years. Details regarding risks that are being assumed, the average workload of the staff (e.g, is overtime being frequently utilized?) and other such information, had it been provided, could have improved the Panel's confidence that the Project's reduced mission operations workforce is adequately staffed when/if the mission goes into an extended phase dominated by anomalies.

The over-guide budget only addressed the roll-off of staff that is planned in the in-guide budget. There are three areas in the view of the Panel that should be further considered:

- Related to the mission operations concern above is the ESA-contributed resources and whether or not there is a clear commitment to continue provision of these resources through the extended mission time frame. The proposal does not provide a plan in either the in-guide or over-guide budget to mitigate the potential loss of this contributed resource should ESA decide to reduce this support in the future.
- Another area of concern is the vulnerability of the GO/AR budget in the event of an unanticipated spacecraft issue that requires a costly mitigation. The Panel recommends that NASA commit to protecting the GO/AR funding line in the future, should such an unexpected situation arise.
- The increasing interest in the astronomical community in multi-messenger astronomy and time domain astronomy will likely change the observing model that has served HST so well. There may well be important cost implications to support for these new operating modes. The Panel would encourage further consideration of the opportunities afforded by including them in the over-guide budget.

ADJECTIVAL RATING FOR TECHNICAL CAPABILITY AND COST REASONABLENESS: **EXCELLENT/VERY GOOD**

**ADDITIONAL REQUESTED FINDINGS**

**1. The effectiveness of the observatory, and its associated operations center and infrastructure in enabling new science, archival research, and theoretical studies.**

STScI and GSFC have been excellent stewards of astronomy's premier observatory. Over nearly 30 years of operations, STScI and the Hubble Project at GSFC have been exemplary in their support of science not originally envisioned when HST was launched. New science has been facilitated by four servicing missions supported by GSFC and the requisite instrument support, calibration, and user support provided by STScI.

Although we were not asked to review the outreach and public education programs in the Project, the HST has been invaluable to the public's understanding and appreciation of astronomy and science in general. The 1000th press release on science results from the Hubble mission occurred on December 20th, 2018. The Hubble also has 100,000's of followers on social media via Facebook, Twitter, Instagram and YouTube.

The MAST archive is the model for all NASA missions. The Archive and Theory programs, independent of new observations, extend and expand the value of Hubble data currently and in the future.

**The Hubble Project should consider the creation of a special archive for delivering theoretical results based on HST observations and archival studies (e.g., simulations and models).**

**A long term commitment is recommended to maintain the Archive and support of continued archival research post the demise of the telescope**.

The Panel cautions the use of and possible future reliance on commercial web services, and associated pay-wall and/or subscription services that may hinder full community utilization of Hubble archive data, which is a public asset. NASA SMD as a whole need to understand the implications of reliance on the commercial sector to provide community services that may impact accessibility and drive investigator costs.

**2. 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 three to five years.**

The efficiency of HST operations is currently at or near maximum. Science results and productivity, as measured by publications and citations, remains one of the highest in astrophysics.

The major technical obstacles that will compromise the efficiency and science mission operations over the next three to five year period are likely gyroscope failure(s) and loss of fine-guidance sensor capabilities. The Project is well prepared for the probable failure of one or more gyros. HST has operated before with two gyros with no significant loss of efficiency or science. The Project is prepared to operate with only one gyro. Indeed they plan to move to one gyro operation after the next gyro failure. Based on their documented plans and presentation, the transition may not significantly affect HST's science objectives.

The panel commends the Project for continuing to look for operational efficiencies and their completed and planned HST life extension initiatives as Hubble ages.

**3. 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 Hubble Project has operated for the past few years with a flat budget which is also projected for the next 2 to 3 years. This budget has recently been supplemented in FY 20 and FY 21 with uncosted carry forward (from GO grants and contracts) targeted toward the grants and fellowship programs. Major gains in operations efficiency may have already been realized. The Panel noted that the mission operations staffing (GSFC) profile has a downward trend in the proposed in-guide budget which may challenge the Project's ability to maintain effective operability of the spacecraft and instruments. However, detailed review of the operations efficiency was beyond the scope of the panel's 2.5 day review.

**4. Notable aspects that would enhance the science return of the mission within its available resources.**

HST has been very responsive to transient events which can be disruptive of regular scheduling. But in the near future HST can expect increased pressure for rapid response driven by time domain astronomy and Multi-Messenger Astronomy. Scheduling of these events will be more demanding and add to the workload. The increased interest in follow-up observations of newly discovered exo-planets also impacts scheduling and in addition is often time critical. **The Project should carefully evaluate the constraint these demands will place on their resources, and solicit community input for a rapid response policy.**

HST is now facing increased stress on the efficiency of its operations over the next 3+ years as one or more gyros may fail and as its instruments age. HST is our only telescope with UV imaging and spectroscopy and will remain so for the next decade or more. **We therefore strongly endorse the UV initiative beginning in Cycle 21 and the new DDT program of UV spectroscopy for star formation and fundamental stellar astrophysics. We urge STScI to**

**solicit community input for a "bucket list" for UV and optical observations that will not be possible with JWST and ground-based telescopes in the next five years or so.**

The Panel supports the Project's effort to transition from IRAF to newer Python-based codes. However, we caution that there be sufficient oversight of these initiatives to provide the community with integrated analysis tools. A universal, general purpose data analysis package for Hubble, JWST and other missions is necessary to produce timely science outcomes that are both robust and reproducible.