2022 Astrophysics Senior Review - *Chandra* Report

PANEL

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EXECUTIVE SUMMARY

The *Chandra X-ray Observatory* continues to fulfill its mission and offer extraordinary science as a general-purpose, facility-class NASA Great Observatory. *Chandra* is delivering unique, cost-effective, and high-impact science, while engaging a broad community of scientists, all more than 20 years after its launch. The scope of *Chandra's* science impact spans nearly every domain in astrophysics, from cosmology and fundamental physics to the impact of stellar flares on the habitability of exoplanets. These science returns arise from *Chandra's* unique and essential capabilities – sub-arcsecond spatial resolution and high spectral resolution – which has no peer in X-ray astrophysics and no replacement on the horizon.

Chandra's capabilities are well aligned with the priorities of NASA's Science Directorate and the recommendations of the 2020 Decadal Survey (Astro2020), and fulfill a major component of NASA's panchromatic capability. Continued high-efficiency operations and robust archives enhance *Chandra's* synergy with other high-energy and multi-wavelength missions (e.g., the *James Webb Space Telescope*) led by NASA and other agencies. The observatory is aging, but the excellent science and operations teams still maintain an observing efficiency of over 70%, near the maximum allowed by the orbit. The team's emphasis on data accessibility within the broader science community (via the easily accessible *Chandra* Source Catalog, CSC, archival/pipeline processed data, software, sonification, and user support) is also commendable.

The *Chandra X-ray Observatory* is not only scientifically and operationally extraordinary, it delivers world-class results year after year from within a very limited budget. This review panel and report unanimously urge adoption of at least a "basic" budgetary over-guide, which is necessary to maintain *Chandra* at its current productive level. This additional investment will preserve *Chandra's* excellence, impact, and community growth. The panel also strongly supports the augmentation over-guides compiled by the *Chandra* team to creatively support diversity, equity, and inclusion (DEI), enhance time domain capabilities, and preserve grant funding levels. At the same time, the panel finds that the baseline funding scenario risks the loss of substantial science reach, out of proportion with the cost savings.

One of *Chandra's* primary instruments, the High Resolution Camera (HRC), experienced an anomaly in early 2022 and was powered down (though all other aspects of the spacecraft continued performing nominally). Within only ten short days, the observatory team had shifted crucial radiation-monitoring functions to the Advanced CCD Imaging Spectrometer (ACIS) and resumed a full schedule of observations. Since then the team has made considerable efforts to recover the HRC and mitigate negative impacts on the observatory. Returning the HRC to full operations is a priority, but should the instrument not be recovered, *Chandra's* science capability remains excellent.

Looking toward the future, the *Chandra* team has begun to devote increased attention to DEI and to develop a set of priorities for increasing participation in the observatory's science and operations. These initiatives are poised to mature into a full strategic plan for

DEI, both internal to the *Chandra* team and in their ongoing outreach initiatives. These efforts will bring the observatory into even closer alignment with NASA's core value of creating inclusive and accessible scientific environments. At this stage in the mission, science legacy planning should be considered. Mission-directed, community-supported special initiatives could provide invaluable, unmatched data from underutilized or fading capabilities and could also provide a forward-looking legacy by addressing precursor science for the next Great Observatories.

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

Chandra provides the community with unique capabilities among astrophysics missions. Chief among these are its sub-arcsecond imaging capability and nine orders of magnitude dynamic range in flux. In addition to these impressive attributes, *Chandra* provides high resolution spectroscopy with its grating instruments and timing capability of 16 microseconds using the HRC (when it is in good health). Over the mission's lifetime, *Chandra* has invested significant resources into calibration which have benefitted cross-calibration efforts with other X-ray facilities and amplified the value of the archival data. The unique capabilities of *Chandra* pair perfectly with the rest of the Great Observatories and forthcoming flagship missions, and there is no planned functional replacement for these capabilities in the coming decade. The synergistic value of panchromatic facilities has been recognized by the Astro2020 Decadal Survey by inclusion of a new "Great Observatories Mission and Technology Maturation Program", to pave the way for a new generation of NASA-led innovation.

Numerical estimates of *Chandra's* scientific impact may be quantified by proposal pressure, community usage and publication statistics. *Chandra* has > 4,870 individual PIs and Co-Is, with an average of 178 new investigators per year. A total of 5,185 US-based research teams have been funded through *Chandra's* Cycle 23, with more than 4,000 young scientists supported and trained in X-ray astrophysics. Through Cycle 23, the oversubscription factors are 5.3 in observing time and 3.5 in proposals. More than 8,925 refereed papers have been published, typically 445 per year since 2003, with nearly 400,000 citations to date.

Chandra's science-ready, processed data are made available to users, and later to the *Chandra* Data Archive (CDA), with high efficiency. The 45 TB archive averages 17.4 TB of downloads per year (between 2011-2020) with queries originating in 108 countries. This level of engagement highlights sustained interest in *Chandra* data. Future efforts to add alert systems and enhancements in the processing pipeline, e.g., to include searches for transient behavior, will further improve time domain astrophysics and complement the Rubin, *Swift*, and *eROSITA* observatories.

In the context of the 2022 Senior Review, the project has outlined an ambitious scientific program that is enabled by the unique capabilities of the observatory. Examples of these, and more detail on recent discoveries, are included in the following sections.

Cosmology and Fundamental Physics: Galaxy clusters represent the most extreme matter overdensities in the Universe. They thus enable powerful tests of the standard cosmological model and offer opportunities for the study of dark matter. Hot diffuse gas, whose X-ray emission is visible to *Chandra*, represents the dominant component of baryonic matter within a cluster. *Chandra*'s sensitive, high-resolution images of this emission, in conjunction with lensing measurements from *Roman*, Rubin, *Euclid* and other forthcoming near-UV to near-IR imagers, constrains the mass-observable relationships required to derive the cosmological information from number counts of galaxy clusters. When applied to large samples of the most massive, relaxed clusters out to z=1, these data provide measurements of the gas fraction – the ratio of gas to the total cluster mass – which provides independent constraints on cosmological parameters, including the Hubble parameter and the dark energy equation of state.

Measurements of the Hubble parameter, both directly at low redshift and indirectly from measurements of the cosmic microwave background and large scale structure, are well suited to test the validity of the standard LCDM cosmology over cosmological time scales. Direct measurements of cosmic expansion derived from relatively low redshift observations have evidenced a persistent discrepancy with those derived from geometric methods. Determining whether the discrepancy is a result of systematic effects in one or more of these methods, or whether it is a signature of new physics, is a major focus of experimental cosmology. *Chandra* data have played a critical role in a promising new method that employs quasars out to high-z as 'standardizable candles', in which a combination of UV and X-ray data enables a direct measurement of the luminosity distance to much higher redshift than is possible using Type Ia supernovae. *Chandra*'s CSC 2.1, and future developments of that resource, will represent a qualitatively new tool for the community to explore the potential of such measurements.

Interacting clusters have shown their potential to serve as cosmological colliders that are capable of putting constraints on the nature of dark matter. By separately mapping the distributions of gas, stars and dark matter in these dynamical systems, one can place limits on interaction cross sections within the standard model and, importantly, any beyond standard model physics within the dark sector. *Chandra*'s resolution and well characterized calibration enable this window into what lies beyond Standard Model physics. Meanwhile, many natural extensions to the standard model provide for axion-like particles (ALPs) that could serve as cold dark matter. A defining characteristic of the ALPs is their interaction with photons in the presence of a magnetic field. *Chandra* measurements of absorption features in the spectra of AGN, which probe the magnetic environment of the hosts, currently provide the strongest constraints on the coupling constant for ALP-photon interactions over the relevant mass range.

Observational probes of the dynamical evolution of galaxy clusters and groups provides insight into the hierarchical nature of structure formation, which is a pillar of the standard cosmological paradigm. An understanding of the dominant processes requires better understanding of cluster physics, including AGN feedback and cooling flows. *Chandra* data directly probe these structures that extend out to redshifts nearing z=7, allowing the study of the evolution of cluster physics over cosmic time.

Galaxy Formation and Evolution: *Chandra*'s superb angular resolution and sensitivity make it a vital observatory to complement other high-resolution multiwavelength facilities (e.g., ALMA, *HST*, *JWST*) in studies of galaxies and their constituents. An example of this synergy addresses an important open question related to galaxy formation and evolution: what is the origin of cool gas in early-type galaxies? In the paradigm where the galaxies co-evolve with their central supermassive black holes (SMBHs), and transition into passive, low star-formation rate (SFR) galaxies, molecular cold gas is expected to form as the hot halos cool. A recent study addresses this question by observing 40 nearby (z=0.001-0.032) early spiral and brightest group galaxies with ALMA and *Chandra*, and finds that the ratio of cold molecular gas to hot gas mass within the central 10 kpc is 10-20%, which is similar to that in brightest cluster galaxies (BCGs) with 10^4 times higher molecular gas masses.

Another example derives from the unknown nature of ultra diffuse galaxies (UDGs). As a subset of low surface brightness galaxies they may be either relics of early type galaxies, having effective half-light radii that are 1.5-4.5 kpc and possibly containing globular clusters (GCs), or they may be dwarf galaxies with low surface brightnesses. By stacking the *Chandra* and UV observations of >450 Coma cluster galaxies, *Chandra* has placed strong limits ($L_X < 9.1 \times 10^{37}$ erg/s) on the hot halos around UDGs. The *Chandra* observations also find no detection of low-mass X-ray binaries (LMXBs) associated with globular clusters ($L_X < 1.1 \times 10^{38}$ erg/s, e.g., the archetypal UDG, Dragonfly 44). These measurements rule out massive dark matter halos (virial mass $\geq 5 \times 10^{11}\ M_{\odot}$), confirming UDGs as genuine dwarf galaxies.

Galactic Centers and Supermassive Black Holes: Recent observations by *eROSITA* have confirmed the previously-observed X-ray (*ROSAT*) and gamma-ray (*Fermi*) bubbles, which are structures that extend ~ 10 kpc above and below the Galactic plane and may be evidence of Galactic nuclear feedback. However, *XMM* and *Chandra* observations of these regions raise questions about the relationships between these structures at different scales. Recent high spatial resolution *Chandra* data have revealed well-delineated "chimneys" extending from the Galactic center towards, and merging with, the Fermi bubbles at 150 pc scales, suggesting that energy is transported from star-forming winds and/or supernova explosions into the bubbles. On ~15 pc scales, *Chandra* resolves bipolar lobes extending into the chimneys. The entropy in these two regions is different, arguing against a smooth transition, but the alignment may facilitate energy transfer from the Galactic center into the Fermi bubbles. A similar, smaller (~1 kpc) pair of X-ray bubbles is seen in the galaxy NGC 3079, with the bubbles also detected in radio and optical H-alpha emission.

Chandra has also been a power-house in observations of accreting supermassive black holes (SMBH) since its launch – this early momentum has not slowed. Accretion onto compact objects is typically accompanied by X-ray emission and the high-energy photons are particularly successful at piercing the obscuring gas and dust at the cores of galaxies. *Chandra*'s long legacy of creating complete samples of active galactic nuclei (AGN) and many successful programs targeting individual systems of high interest have shown important connections between SMBH/AGN and their host galaxies. These appear to be linked via the system mass (measured via stellar masses and the dark matter halo mass) and feedback from current or historical accretion activity traced, for example, by features like the Fermi bubbles mentioned above.

Combining deep *Chandra* observations with multi-wavelength observations from other ground- and space-based observatories further leverages the *Chandra* observations and reveals the full spectral energy distribution, elucidating the physics driving emission from the accretion disk, jet, corona, and surrounding hot gas. A particularly striking recent example is the large, multi-wavelength campaign targeting M87*, the SMBH in the Virgo cluster, famously imaged by the Event Horizon Telescope. This contemporaneous campaign, to which *Chandra* was a key contributor, offers a spectacular "golden" spectral energy distribution (SED) that traces emission from near the black hole's event horizon and then out along the jet over seven decades in wavelength and physical scale. An equally impactful suite of *Chandra* observations is planned for upcoming cycles to observe candidate binary SMBH, which may offer the best targets for searches for new gravitational wave signals with pulsar timing arrays and the upcoming LISA mission. These are complemented by planned observations of gravitationally lensed targets in Abell 2744 (visible out to z>7) in an approved joint *Chandra*/JWST very large project.

X-ray Binaries and Neutron Stellar Structure: The death of a star in a binary system is the primary channel for the formation of X-ray binaries, which consist of a normal star and a compact object, typically a neutron star (NS) or black hole (BH). *Chandra* has provided key results in our understanding of X-ray binaries, which are central to probing binary star evolution. For example, BH-LMXB GRS 1915+105 has recently become historically faint – up to one to two orders of magnitude in 2019 -- likely driven by heavy obscuration of a failed disk wind. This could perhaps also explain analogous "occultation" events observed in Active Galactic Nuclei, such as those observed in Type 2 AGN. These systems are the progenitors of a variety of astrophysically important descendants, including gravitational wave sources, stripped-envelope supernovae, gamma-ray bursters, and ultra-luminous X-ray sources.

The X-ray emission from high mass X-ray binaries (HMXBs) in galaxies at z>10 may be responsible for heating the intergalactic medium (IGM) in the early universe. Based on X-ray binary synthesis models, the formation and evolution of the HMXBs is metallicity-dependent, where low metallicity environments lead to weaker stellar winds and tighter binary orbits. Recent *Chandra* observations of the integrated X-ray emission from nearby low-metallicity, high-redshift analogs and stacking results from high redshift galaxies confirm a metallicity-dependent X-ray scaling relation. Detailed investigations of individual X-ray binaries (>1300) within 55 nearby galaxies, made possible by *Chandra*'s exquisite sub-arcsecond resolution, shows that the luminosity distribution of XRBs also depends on metallicity, Additionally, the cross-correlation of a compiled catalog of nearby (≤40 Mpc) galaxies (HECATE) with the CSC 2.0 results in ~300 galaxies with >600 ULXs, with a higher ULX frequency in low-metallicity star-forming galaxies. Studies such as these highlight the complementarity to upcoming *JWST* observations and 21-cm radio surveys (e.g., HERA, SKA), which will target the high-redshift Universe.

Understanding the thermodynamic properties of neutron stars provides information regarding the NS equation of state, which cannot be reproduced on Earth due to the extreme densities found in their interiors. Key results from *Chandra* include measurements of the thermodynamic properties of neutron stars via cooling curves – these observations have played a leading role in characterizing the nature of the superfluidity of the NS core. *Chandra* measurements of low mass X-ray binaries located in globular clusters have determined a neutron star radius of about 12 km, along with the first constraints on two parameters determining the NS equation of state. Their location within the globular clusters allowed an accurate determination of the distance to the objects, and *Chandra*'s spatial resolution was able to handle crowding around the NS, enabling a measurement that no other observatory could perform.

Stellar Explosions, Stellar Collision, Their Progenitors, and Their Aftermath: Understanding the mechanism of core-collapse, connecting various supernova subtypes to their progenitor properties (including binarity), and understanding the post-explosion evolution from days to centuries after the event have been long-standing goals of supernova research, and *Chandr*a observations continue to provide unique and crucial insights.

The picture of a convective supernova engine powered by neutrino heating has gained strong support from newly-reported detections of stable titanium and chromium in the iron-rich plumes of the Cas A supernova remnant, discovered in deep archival *Chandra* data. Further insight into the progenitor of the Cas A supernova comes from the recent detection of Mn, implying subsolar metallicity of the progenitor. The mass-loss rate required for a low-metallicity star to lose most of its H envelope (as the Cas A progenitor did) is incompatible with a single-star scenario and requires some sort of companion. The non-detection of a companion from HST and Pan-STARRs raises the possibility of a compact companion.

Upcoming *Chandra* observations will extend this insight into supernova progenitors through the study of late-time X-ray properties of nearby extra-Galactic SNe. As the shock wave from the supernova explosion travels outward at ~10^4 km/s, it interacts with the material shed earlier and earlier in the progenitor star's history. This interaction produces radio and X-rays, which together can be used as a time machine to trace the mass-loss history of the progenitor. Recent *Chandra* observations detected a Type Iax SN candidate in our own Galaxy, and it remains the nearest such object for follow-up observations. Upcoming programs to study a sample of nearby radio-bright SNe and to further study SN 2004dk, whose late-time emission suggests an interaction of fast and slow winds from the progenitor, promise additional and significant progress in this area.

The detection of the binary NS merger GW170817 with LIGO and Virgo, and the subsequent study of its electromagnetic emission, opened up a new channel of astrophysics, with *Chandra* providing unmatched insights. Recent *Chandra* observations detect emission at levels inconsistent with jet-only models, suggesting a kilonova afterglow or accretion onto the merger remnant. *Chandra* will continue to monitor GW170817 in Cycle 23 and beyond, as well as follow new GW detections in LIGO/Virgo O4.

Stars and Planets: Since the last senior review in 2019, *Chandra* investigators have used the observatory's unique capabilities to study the impact of stellar flares on planetary atmospheres, and the impact they have on planetary masses themselves. These have fundamental consequences for the possible evolution of life around such stars. Observations with HETG recently provided the first evidence of a coronal mass ejection from a star other than the Sun, providing connections to the planetary science of our own solar system. Archival data and upcoming observations continue to enable excellent science in this area, including measurements of X-ray emission from Uranus and the Galilean satellites of Jupiter.

ADJECTIVAL RATING FOR SCIENCE MERIT: **EXCELLENT**

CRITERION B: RELEVANCE AND RESPONSIVENESS

The 2020 NASA Science Mission Directorate Science Plan: The Proposal comprehensively responds to the 2020 SMD Science Plan, “Science 2020-2024: A Vision for Scientific Excellence,” by addressing all the Priorities in multiple ways. Priority 1 is *Exploration and Scientific Discovery* – the Mission’s science program shows outstanding balance between all areas of astrophysics (Strategy 1.1). Although planetary exploration is a lower Mission priority, it nevertheless addresses the Exploration theme of Priority 1 with studies of the solar system and synergistic work studying stellar flares in other systems, for example, the first discovery of coronal mass ejection beyond the sun (Strategy 1.2). Priority 1 is also promoted by *Chandra*’s participation in emerging fields (Strategy 1.3) such as gravitational wave and time-domain science and the Event Horizon Telescope breakthrough observations. Priority 2 on *Innovation* is also addressed by the culture of collaboration, and commitment to community peer review that prioritizes innovation (Strategies 2.1, 2.2). As well, the Observatory is continually seeking to improve user access, for example, by developing and enhancing the CSC 2.1. Priority 3, *Interconnectivity and Partnerships*, is clearly promoted by the active and evolving partnerships with other observatories including *HST*, NRAO, *XMM*, and Rubin / SDSS (Strategies 3.1, 3.2). These include working with NASA, NSF, DOE, and others (Strategy 3.3), thereby clearly increasing opportunities for research institutions worldwide to contribute to SMD’s mission (Strategy 3.4). Altogether, these support Priority 4, *Inspiration*, by enabling diverse members from a wide variety of communities to use *Chandra* data and advance science (Strategy 4.1). The CXC also has an admirable and longstanding public outreach program which inspires the public and reaches diverse audiences (Strategy 4.2).

The 2020 Decadal Survey: “Pathways for Discovery in Astronomy and Astrophysics for the 2020s” (Astro2020) includes recommendations on Diversity, Equity, and Inclusion, and Workforce Training. The *Chandra* mission addresses these by monitoring and promoting gender equity among proposers and their workforce, with proposals now being evaluated under double-blind review, as well as running a highly productive public outreach program. The proposal also addresses Astro2020 concerns about Investigator Grants and Programmatic Balance, with GO funding siloed.

In addition, the CXC has outstandingly addressed Astro2020 recommendations regarding Data Analysis and Data Archiving, with improvements to the *Chandra* archive and continued development of the *Chandra* Source Catalog and its comprehensive, science-ready data products. These efforts make the *Chandra* data accessible and user-friendly, even for novice users. Highlight include:

- The second release of the *Chandra* Source Catalog (CSC 2.0) is a valuable resource with >400,000 sources. Upcoming plans to increase the archival value by partnering w/ SDSS also offers a novel and creative approach.
- The development of CSC 2.1 will provide high-level data products in an analysis environment. It includes the expansion of the archival data system, making accessing, downloading, and visualizing the data intuitive, and enhances the efficiency of scientific analysis, greatly multiplying *Chandra*'s productivity.
- Maintenance and updates to the CIAO tools, threads, and documentation continue to meet and anticipate user needs. The addition of Jupyter notebooks also makes *Chandra* data analysis easier for everyone from new users to the experienced high-energy research community.
- Boosting the archive interoperability with other multiwavelength archives, the CDA now complies with International Virtual Observatory Alliance standards. The *Chandra* bibliography cross-links archival observations with literature through the Astrophysics Data System (ADS), and has adopted Digital Object Identifiers (DOIs) for archival observations.

The SMD calls out three Astrophysics science themes: *Physics of the Cosmos* (PCOS), *Cosmic Origins* (COR) and *Exoplanet Explorations* (ExEP). These synergize strongly with those of Astro2020, which prioritizes: A. *New Windows on the Dynamic Universe*, B. *Unveiling the Drivers of Galaxy Growth*, and C. *Pathways to Habitable Worlds*. As seen above, *Chandra*'s science programs address these priorities in many ways, for example: (A/PCOS) using supernovae to trace cosmological structure, and detailed studies of compact objects that link to time domain astrophysics and gravitational wave sources; (B/COR) studies of the connection between fast radio bursts and AGN or ULXs, and understanding the growth of supermassive black holes over cosmic time, e.g., multiple AGN in merging galaxies and searches for active SMBHs in *JWST*-detected galaxies at $z>7$; and (C/ExEP) studies of young stellar populations and stellar flares that affect the evolution of exoplanets and their habitability, and studies of our own solar system.

Chandra as a Great Observatory: More broadly, *Chandra* plays a critical role as a facility-class Great Observatory that is a powerhouse for addressing a broad range of science questions. The Senior Review proposal clearly demonstrates that it continues to deliver and fully support the goals of the NASA Astrophysics Division and Astro2020. The power of a facility-class observatory such as *Chandra* operating in tandem with other Great Observatories has been explicitly recognized by Astro2020, which recommends a new "Great Observatories Mission and Technology Maturation Program" to pave the way for a new generation of Great Observatories.

The proposal adequately addresses relevance to NASA's core value of inclusion and alignment to Strategy 4.1 of the SMD Science Plan. The proposal offers statistics that demonstrate both contemporary and historic gender diversity on the CXC team. Other axes of diversity are less-well characterized, with quantitative metrics for inclusion beyond gender so far unavailable. *Chandra*'s public-facing programs effectively nurture diversity of thought and inspire future scientists; *Chandra* contributes significantly to scientific literacy, public outreach and STEM education and adds to training the nation's workforce in STEM in several important ways. The proposal outlines the activities of the project's public communications group, including quantitative assessments of the scope and impact of that public outreach.

Chandra has had a *direct* impact on the careers of young scientists, with 4,463 young scientists supported by *Chandra* (ranging from undergraduates to postdocs) and 452 PhD theses (1999-2021) have included *Chandra*-related research. As noted above, the *Chandra* team has worked to ensure easy access to the archival data and the CSC, and supports the broader astrophysics community through their provision of CIAO software, easy-to-use Jupyter notebooks, and well-written documentation. Collectively, these initiatives make *Chandra* data uniquely accessible to the astrophysics community.

Prioritized Mission Objectives: Meanwhile, the *Chandra* team has made excellent progress on all prioritized mission objectives (PMOs) from the 2019 Senior Review:

- PMO-1: Continue *Chandra*'s scientific excellence and impact in accord with top level NASA goals.
- PMO-2: Provide complete, well-calibrated science data products and analysis tools to the science community and make *Chandra* data and documentation available worldwide.
- PMO-3: Ensure the health, safety and productivity of the Observatory.
- PMO-4: Utilize budgetary resources efficiently to maximize *Chandra*'s scientific productivity and service to the scientific community.

The continued high oversubscription on *Chandra* is a clear signal of its success in conducting community-driven science (PMO-1.1) as is its responsiveness to numerous DDT requests. The mission has optimized observing opportunities (PMO-1.2) by restoring Very Large Programs (>1Ms) in Cycle 19 and allowing the allocation of time for them from the following cycle. The CXC has partnered with SAO to join the SDSS-V collaboration in order to obtain spectra for optical and infrared counterparts of *Chandra* X-ray sources. The CXC will provide links to the SDSS spectra, and provide source classification and redshift as a *Chandra* Source Catalog (CSC) data product. The CXC has optimized proposal opportunities (PMO-1.2) by instituting dual-anonymous peer review, which started for Cycle 22.

The *Chandra* team is working to release version 2.1 of the CSC in 2023 (PMO-2.1). This new version will contain over 120,000 more sources than version 2.0, and will be navigated by impressive and full-featured software that allows for both quick, basic analysis and detailed exploration and aggregation of source properties; the availability of Python Jupyter notebook templates will allow for reproducible data mining and analysis. The CXC continues to add advanced analysis features to the Sherpa and DS9 software packages (PMO-2.2). The panel also commends the CXC for its continued support of the online CIAO documentation. The clear, step-by-step guides to data reduction and analysis make the world-class data taken by *Chandra* accessible even to undergraduates.

The CXC meets its goal to deliver data to observers in less than two days (PMO-2.3), achieving a median delivery time of ~20 hours. *Chandra* continues to excel in the calibration domain (PMO-2.4), using 5% of observing time to maintain effective area calibration to better than 5%. The mission participates with other X-ray observatories to observe standard astrophysical calibration targets, which are analyzed by the International Astronomical Consortium of High Energy Calibration (IACHEC). Derived fluxes among these observatories agree to within 10%.

Chandra observing efficiency has remained high (>70%) despite increasing thermal constraints (PMO-3.1). To further the goal of maximizing observing efficiency, the team has developed precise thermal models of the observatory and enhanced mission planning tools to accommodate temperature constraints. Infrastructure improvements to the mission scheduling software pave the way for increased use of automation. The CXC has taken multiple proactive steps to maximize the observatory lifetime (PMO-3.2), including: on-board management of angular momentum unloading that minimizes thruster use; expanding the coverage region for the Sun Position Monitor; updating software to compensate for the increased background of the star camera (something the vendor said was too difficult); and enhancing monitoring tools to anticipate anomalies.

The mission continues using best practices to optimize efficient use of funds (PMO-4.1), which necessitated reducing CXC staff by 6 FTE in FY21. They also merged systems engineering and operations management under one contract with Northrop Grumman to lower expenses. *Chandra* issues grants promptly, typically within 2-to-3 weeks of observation (PMO-4.2), and it leverages its position within SAO to have grants administered by an SAO department for which the CXC is not directly charged.

In addition, *Chandra* has added a new goal, PMO-4.3, to address DEI both internally and externally. The stated objective is to “increase the diversity of CXC staff, accessibility of *Chandra* data, and inclusiveness of our relations with the scientific community.” We commend the team for introducing a new PMO to address DEI and we support its over-guide augmentation to begin a summer internship program for student-faculty groups at

MSIs with underserved student populations. To achieve this new PMO, we encourage the *Chandra* team to develop a strategic plan for DEI, with both inward-looking and outward-looking components that robustly align with NASA's core value of Inclusion and SMD Strategy 4.1. We encourage the team to provide detailed assessments of its DEI activities in SR25 and note that Astro2020 provides useful framing and guidance.

2019 Senior Review Response: *Chandra* has also made excellent progress addressing the 2019 Senior Review (SR19) findings:

(A) SR19 recommended a budget increase commensurate with inflation. NASA augmented the CXO budget including a grants increase, but did not augment *Chandra*'s staff budget, which resulted in the CXC reducing staff by 6 FTE in FY21.

(B) A mechanism for regular addition of cool targets was recommended by SR19. *Chandra* has added an additional call to take place in 2022, although a portion of that call is geared toward HRC, which may no longer be viable.

(C) In a very strong response to the SR 19 recommendation to coordinate with transient-optimized surveys, the CXC held a workshop on time-domain science and established a Time Domain Working Group. An over-guide augmentation request is provided to develop capabilities to quickly and autonomously identify transients in new *Chandra* observations, based on the recommendations of the working group.

(D) After an extensive study of the risks and benefits, the *Chandra* team decided against a bake-out of ACIS to reduce contamination on the optical blocking filter. This contamination reduces the effective area of ACIS at low energies. Given the uncertainty in the chemistry and behavior of the contaminant, the outcome of such a bake-out is uncertain and could include a catastrophic failure of the instrument. The risks therefore were not considered justified.

(E) The CXC team weighed the benefits and costs of carrying out mission-directed observations to contribute to its final science legacy, The team felt that such observations were in conflict with its traditional community-driven observing program, which includes using DDT to respond to requests from the community to observe transient events, demand for which is increasing. As noted below, we encourage the CXC to consider this again and think strategically about legacy programs and programs to perform precursor science for the next suite of Great Observatories. The CXC team should think broadly about collaborations or initiatives that would support this type of mission-directed observations.

(F) In considering longer-term decommissioning, the team has implemented all of the following: moved the development of Sherpa to the open-source facility Github; made a major revision of the Project Data Management Plan to provide a pathway to deliver the archive to HEASARC; and planned for all *Chandra* software and documentation to be preserved on HEASARC and/or open-source repositories like Github.

ADJECTIVAL RATING FOR RELEVANCE AND RESPONSIVENESS: **EXCELLENT**

CRITERION C: TECHNICAL CAPABILITY AND COST REASONABLENESS

Operating Cost and Cost Efficiency: *Chandra* has exceeded its original planned lifetime by nearly two decades and continues to return extraordinary science per dollar and maintain over 70% observing efficiency. Most of the systems remain healthy, but several are showing the signs of an aging observatory. Component failures have been mitigated to minimize impact to operations, but over time the workload to the flight and science teams has increased. Thermal insulation has degraded, and several systems (e.g., aspect camera, ACIS electronics, propulsion tanks and thrusters) require management to keep temperatures within acceptable ranges. Temperatures are managed using attitude adjustments, and dwell time restrictions are necessary, reducing the ability to provide uninterrupted extended observing time. This has greatly increased the complexity of mission planning. To make mission planning sustainable, additional scheduling tools must be developed. A proposed over-guide ("basic") provides two Flight Operations Team (FOT) software engineers to support such tools and enable continued safe and efficient operations.

Budget Challenges and Opportunities: The in-guide budget proposed for *Chandra* is flat between FY22 through FY27. Flat budgets are often accommodated by increased operational efficiencies gleaned over the years by large projects in "steady state" operations. However, for *Chandra*, the aging spacecraft has required increasing attention as evidenced by equipment reconfigurations and flight software patches. It is evident that the staff levels must be maintained to sustain the current level of exceptional productivity, and in fact should be increased slightly to enable continued safe and efficient operations. However, federally mandated Cost of Living Adjustments (COLA) amount to more than 10% from 2022-2024, and 2.5% thereafter. While this mandate applies to the SAO staff, cost of living and merit increases for all staff including contractors must be accommodated within the flat baseline budget. The consequence is a severe reduction in staff, currently estimated at ~30 FTEs by 2027. Such a dramatic cut (24%) in staff would have serious likely consequences, some of which are:

- Observing efficiency reduced from 70% to ~50-60%
- Coordinated or constrained observations reduced from 35% to <10%
- Fast-turnaround ToOs eliminated
- Reduced support to proposers, observers and the community. (Note that this support function serves to "level the playing field" for all *Chandra* users.)

Given the fact that *Chandra* provides unique and necessary capabilities with no replacement on the horizon, the panel strongly believes that *Chandra* should be funded at a level that maintains and maximizes its science return. *The panel unanimously urges adoption of the proposed over-guide "basic" (C.2).* This over-guide would add 2 Flight

Operations Team engineers to enable safe and efficient operations of the spacecraft, and would provide for level staffing from FY23-FY27.

Three other over-guides are meritorious and should be considered. In order of panel priority:

- C.3 Over-guide–Time domain science. This would support one software engineer to enhance the data processing pipeline to search for transient behavior, as well as to identify any *Chandra* Source Catalog sources that match transient event alerts (e.g., from Rubin, *Swift* or *eROSITA*.)
- C.4 Over-guide–DEI Initiative. This provides resources for the *Chandra* Faculty/Student internship program, to engage students and faculty from Minority Serving Institutions in *Chandra*-related research projects.
- C.5 Over-guide–*Chandra* Grant Funding. This proposed budget over-guide augments *Chandra* grants during FY23-27 to restore the losses due to inflation. This also adds funding for an anticipated increase in observing efficiency due to *Chandra*'s evolving orbit. The panel acknowledges that GO funding has a direct impact on the science productivity of the mission.

Health of Spacecraft and Instruments: A significant change in observatory capability occurred recently when the High Resolution Camera (HRC) was taken offline as the result of a sudden anomalous power configuration. The HRC was used both for science observations and to monitor the radiation environment for the spacecraft. These radiation monitoring functions are now being covered by ACIS, and *Chandra* has resumed science operations. The science and engineering teams are analyzing the HRC anomaly, and there are approaches by which HRC might be returned to service. These are being actively pursued.

In the case of the permanent loss of HRC, there would be an unfortunate loss of capability for the observatory. HRC provides high timing capability (as low as 16 microseconds), and with its high spatial resolution and low energy sensitivity HRC stands poised to return science of high impact if it can be brought back online. Recovery of HRC is highly desirable, but without it, *Chandra* will continue to successfully fill its unique, crucial capability as the only high-sensitivity, high-spatial resolution X-ray observatory in operation now and likely for the next decade or more. *This Panel unanimously affirms the continued scientific value of Chandra even if the unfortunate loss of HRC is permanent.*

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

ADDITIONAL REQUESTED FINDINGS

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

Chandra has a successful operating model and has maintained high science productivity throughout its lifetime. Given the mission's current technical challenges, including increasingly complex thermal constraints driving mission scheduling and the impacts of anomalies, it is a credit to the commitment and ingenuity of the *Chandra* team that observing efficiency remains over 70% and that science productivity is high. *Chandra's productivity provides excellent value for NASA's investment.*

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 five years.*

The degradation of the spacecraft's thermal environment poses the most significant obstacle to maintaining the efficiency of science and calibration operations. The scheduling and operations team has consistently demonstrated a remarkable degree of ingenuity, anticipating and mitigating the impact of the thermal constraints on the science operations while at the same time providing excellent stewardship of the observatory. *The processes and people that are in place provide a high degree of confidence that the observatory's science objectives will be met over the next five years. The committee finds that any reduction in this team will result in a commensurate reduction in their ability to maintain the cadence of science observations and to respond to anomalies.*

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 committee finds that the team's stewardship of the observatory has been uniformly exceptional, and extends from the maintenance of the telescope and instruments to the careful stewardship of the data. The talent and dedication of the team has resulted in a rich reserve of archival data, and will ensure that *Chandra's* unique capabilities provide continued discoveries over the next several years.

The committee finds that *Chandra* has provided excellent scientific return on its investment. Furthermore, the committee finds that the marginal cost of the proposed over-guide budget is extremely well justified by the unique capabilities of the observatory and the maintenance of its scientific productivity.

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

A. Development of a strategic plan for Diversity Equity and Inclusion (DEI).

As noted above, there is good work in the outreach program and in promoting gender diversity, but other axes of diversity, within the CXC and also outward-facing, could be more systematically addressed. A purposeful strategic plan would be helpful in addressing the new PMO 4.3.

B. Given the aging observatory, Chandra should consider a mission-directed observation or set of observations to contribute to its science legacy. This might include a partnership with GTO teams and GTO time, in combination with DD time, or leverage other creative solutions.

As the observatory ages, science legacy planning becomes essential. We suggest reviewing programmatic allocations of time to allow for *mission-directed, community-supported strategic initiatives* to ensure appropriate legacy datasets for underutilized or fading capabilities, and/or to pursue precursor science for the next generation of Great Observatories.

There are a number of ways the new Director could explore options for obtaining time for such an initiative, for example through collaborations with GTO teams and leveraging the upcoming low perigee observing-time bonus, as well as DDT. It may also be useful to review impact metrics for LP and VLP programs to determine whether they still fulfill their functions relative to the urgency of creating legacy datasets. A community-driven study of the options (HETG, soft-band, etc) would determine what is most needed for the broadest user base or most urgent for the precursor science for the next Great Observatories.

5. *If the HRC is never recovered, is Chandra still worth operating?*

The operations and science teams have invested considerable effort to troubleshoot recent problems with *Chandra*'s High Resolution Camera (HRC), and to mitigate negative impacts on the observatory while options for recovery are explored. Based on the response of the observatory team and their longer term outlook, it is clear that should the HRC not be recovered, or suffer a subsequent catastrophic failure in the course of recovery efforts, the science capability of the *Chandra* X-ray Observatory remains excellent.

HRC accounts for 6.7% of the allocated GO time. Though there are multiple excellent science cases that exploit its unique capabilities, the majority of the observatory's scientific observations are collected with the ACIS instrument. In addition to science returns, HRC offers important radiation monitoring functions, but these have been successfully migrated to ACIS to keep the observatory healthy and safe. Indeed, the HRC anomaly was detected on 9 February 2022, and *Chandra* resumed a full schedule of science observations with ACIS only ten days later on 20 Feb 2022.

Recovery of HRC is highly desirable – this instrument fully samples the *Chandra* point spread function, which helps mitigate pile-up, offers excellent spatial resolution and also high timing resolution – but without it, the mission will continue to successfully fill its crucial capability as the only high-sensitivity, high-spatial resolution X-ray observatory in operation right now, and likely for the next decade or more. Hence, we conclude that the *Chandra* mission will remain highly productive and offer excellent science return even without recovery of the HRC.