# 2016 Chandra X-ray Observatory Senior Review

**22-24 March, 2016**

## PANEL

**Chair:** Donald Kniffen (Universities Space Research Association, retired)

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## FINAL REPORT DELIVERED TO

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# Executive Summary

Launched aboard the Shuttle in 1999, the Chandra X-ray Observatory (CXO) is the third of NASA's Great Observatories to be placed on orbit, and is continuing to function efficiently with a large community of users. Chandra is widely recognized for its excellent sensitivity and spatial and spectral resolution, allowing a study of very distant sources in the early universe, as well as those in our own Milky Way. Operated for NASA by the Harvard-Smithsonian Chandra X-ray Center (CXC) in Cambridge, Massachusetts, Chandra is now in its 17th year of operation. There appears to be no impediment to many more years of X-ray observations under the CXC stewardship. The 2016 Senior Review Panel enthusiastically endorses the recommendation to extend the mission through 2020 and beyond.

As an X-ray mission, Chandra provides information on the hottest and most energetic objects in the sky, both near and far. This capability has allowed a broad range of astrophysical studies from galaxies, to stars and planets (including exoplanets), as well as exploration of the behavior of matter and energy above nuclear densities. Looking to the years ahead, Chandra aims to compile a broad range of catalogs and legacy data to guide future studies in all branches of astronomy and astrophysics. More recently, emphasis have been the study of the origin and evolution of supermassive black holes and their host galaxies.

The many successes of Chandra have been due in no small measure to the dedicated and highly capable staff who continue to encourage and support users through opportunities to obtain data and observations to pursue a broad range of interests, and support the users in analyzing and publishing their findings. The staff has been very productive in developing analysis software and other tools to support their efforts. The CXC continues to be highly successful in their support of the scientific community in all phases of participation in the use of the CXO and in monitoring the Observatory and maintaining its health and safety. In the March 2016 review, the Panel developed the following responses to the charges to the 2016 Senior Review Panel described in Sections 1-6 below:

***1**. Consider the Prioritized Mission Objectives (PMOs) described in the 2016 Senior Review proposal, and assess the scientific merit and expected science return of the observatory over the next 2 to 4 years.*

The Senior Review Committee (SRC) finds that the Chandra team continues to provide excellent observatory stewardship to the community. During their presentations, the Director and the Project Scientist have convincingly demonstrated to the SRC that the Observatory is positioned to allow the community to fully utilize the CXO capabilities in the upcoming cycles. More specifically, the SRC

acknowledges two major initiatives implemented since the 2014 Senior Review. These initiatives are expected to significantly enhance the science return of the observatory over the next 2 to 4 years.

- *The release of the second Chandra Source Catalog (CSC).* This is an extremely important effort that will provide the scientific community with an important and valuable tool. Compared to the first version of the catalog, the number of sources will increase from 100,000 to 350,000, in part due to including data from additional years of operations and in part due to now stacking (majorly) overlapping observations, thereby increasing exposure times and sky coverage. The ensuing product will complement earlier catalogs in terms of depth, sky coverage, energy range, and temporal coverage (e.g., ROSAT, XMM-Newton, INTEGRAL). The CSC will be a unique and important database, enabling studies of a variety of astrophysical objects both on its own and in combination with other multiwavelength surveys. This is a well executed project by an expert team and the results will be one of the most significant CXO legacies. *The SRC considers this a high priority project for the next 2 years.*

- *The establishment in Cycle 18 of the Joint Large Proposal (JLP) program.* The JLPs may be one of the most visionary recent actions of the CXC team, providing successful proposers with guaranteed Chandra observations conditional on securing additional data through proposals to other multiwavelength observatories (e.g., ALMA, HST, NOAO, NRAO, NuSTAR). The idea overcomes the hurdle of double jeopardy, in particular the problems of out of phase proposal cycles and the uncertainty of a second observatory approval without the guaranteed time of the first. While the community had largely solved this problem for smaller programs, large programs still suffered from this issue. Having conditionally approved CXO observations, scientists will be able to write stronger proposals for supporting observations across the broad suite of observatories.

Further, we expand on additional actions and concerns we feel will impact the next two years of Chandra science.

- *Flexibility in adapting to a changing landscape*. The CXC team has been very flexible and responsive in adapting the Call for Proposal to reflect the input from the Chandra User Committee (CUC) and the community to maximize scientific output. As an example, the CXC team discontinued the X-ray Visionary Program (XVP) during Cycle 18 following the recommendations of the CUC, who found that there was a large backlog of compelling and highly oversubscribed Large Programs (several 100 ks, vs. typically >1 Ms for XVPs). Relatedly, the minimum amount of time required for Large Programs was increased from 300 ks to 400 ks.

- *Seamless continuation of the CXO observing program despite age-related degradation issues.* The SRC highly commends the stewardship of the CXC in avoiding losses of observing time by effective mitigation of multiple issues (see Section 4). We endorse and commend the CXC efforts to seek community input for scientific planning via workshops and white papers, and for sustaining the CXO data quality with frequent updates to data calibration and software development.

- *Positioning CXO to exploit synergies with future observatories.* CXC is planning to incorporate time from recently launched missions (Hitomi) and future missions (JWST) in future GO programs.

- *GTO allocation*. The SRP recognizes the importance of the services provided by the Instrument Teams, and strongly commends them for maintaining a highly productive and well calibrated instruments. The committee, however, would like to express concerns, similar to the ones expressed in 2010, 2012 and 2014 by the then Senior Review panels regarding the continuing allocation of 2.45 Ms/yr of GTO time, now more than 15 years after launch. This allocation represents a large percentage (11.4%) of observing time each year, and is the result of an agreement made 22 years ago, several years prior to the launch of Chandra. The allocation is set to continue through the lifetime of the mission. Included with the GTO time allocation is ~$1.8M/yr for GTO data analysis funding. The SRP finds that publication rates related to the GTO observations are comparable to GO observation publication rates. However, the SRP has a number of concerns regarding continuation of the GTO policy. The panel believes that a thorough review and revision of this policy is warranted. The panel endorses the premise that there should be no changes to the GTO policy, where the safety and proper functioning of the instruments should might be compromised.

- *GO budget.* The SRC finds that the CXO scientific return in the next two years strongly depends on the preservation and enhancement (at least according to inflation) of the GO program budget (see Section 5 for a more detailed description).

## *2. Assess the observatory's progress made toward achieving the PMOs described in the 2014 Senior Review proposal.*

**PMO 1:** *"Continue Chandra's scientific excellence and impact in accord with the top level NASA goals"*

The panel finds that Chandra continues to be a highly productive observatory with high impact on most of the science fields identified in the NASA Roadmap, the SMD Science Plan and the 2010 Decadal Survey. The observatory is operated at essentially maximum possible efficiency.

Thanks to the stewardship of the observatory and the forward-looking approach to mission operations and problem mitigation, the scientific discovery space has not been significantly affected by the increasing limitations on spacecraft operations to date.

The success in enabling science is well documented by the number of high-impact discoveries announced during the 2014-2016 time frame, the continuing high yield of papers per observation and exposure time, and the roughly constant oversubscription rate.

The Chandra team has engaged the CUC and the broader scientific community by soliciting white papers and organizing regular workshops to continually assess the scientific footprint of the observatory and identify the key science questions the observatory should be addressing. The approach the observatory leadership has taken throughout the entire mission is to respond to -- as opposed to drive -- the community input by ensuring, as much as possible, that there are no programmatic impediment to the smooth execution of proposals addressing the key scientific questions raised by the community. This includes introducing new proposals categories, as reflected in the Call for Proposals. The committee supports this approach and would like to see the team to continue these formal assessments of the scientific impact by the observatory to ensure that legacy science projects can be completed through the current means of time allocation.

**PMO 2:** *"Engage the science community by providing complete, well-calibrated science data products and analysis tools and by making Chandra data and documentation available worldwide."*

The Chandra Interactive Analysis of Observations (CIAO) continues to be both powerful and accessible. The development of additional science threads and scripts has improved the workflow and ease of use. The panel concludes that ongoing work on software development and calibration addresses the needs identified by the community through the CUC and help desk and in previous SRs. We commend the team for the rapid turnaround in initial data delivery and in the rapid response of help desk requests.

Periodic release of new versions of the user software (CIAO, MARX) and continuing timely upgrades to the CALDB are essential to increasing the versatility of the observatory and in enabling new types of science proposals. The Chandra team continues to provide software and calibration upgrades at the rate necessary to enable prompt reduction and analysis.

The broad user base and the number of new investigators in each call for proposals supports the notion that Chandra is engaging the entire scientific community. The panel finds that no field of science appears to be underserved and that productivity is high across fields, as reflected by the publication rates. The panel commends the Chandra team for collecting detailed metrics and finely granulated publication data.

**PMO 3:** *"Ensure the health and safety of the Observatory through continuous monitoring monitoring, use of proven procedures by highly trained staff, carefully considered and tested responses to anomalies, and proactive planning to increase operational efficiency and anticipate problems."*

The Chandra team has done an outstanding job of monitoring and preserving the health and safety of the observatory under the challenges posed by an aging spacecraft. The implementation of cross-training and automation in ground and flight control and the upgrade to modern hardware and virtualization of control systems have been important achievements over the 2014-2016 time frame that serve to increase the

productivity of the workforce and to ensure the long-term preservation of core competencies by the observatory staff.

The extensive efforts at understanding and modeling the observatory subsystems' aging efforts have allowed the Chandra team to mitigate the aging 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. These activities have resulted in maintaining the excellent observation efficiency of nearly 70% -- the same as in the earliest years of the mission.

The panel agrees with the conclusions of the 2015 Operations Review that the observatory is being run effectively and that mission planning as implemented is achieving the goal of optimizing the observing efficiency.

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

Since launch, the Observatory has significantly reduced the operations budget, as expected for a mission in its extended operations phase. Specifically, since launch, the Chandra staff has decreased by over 40%. An additional cut of 9.6 FTE is projected between FY17 and FY20. In addition, thermal degradation is slowly posing more observational and operational constraints. In spite of this, the Observatory remains extremely healthy, as evidenced by the following facts:

1. the observing efficiency has remained maximal, with essentially all science observations executed, with all required constraints;

2. the proposal oversubscription rate remains high, with a mean oversubscription factor of 5.5 that has remained steady for the past decade; larger oversubscriptions, close to 10 in some Cycles, exist for Large Programs;

3. each Cycle sees a significant number of new investigators, with a mean value of 190 new investigators (PI's + Co-I's) per year on accepted programs;

4. the number of published papers remains high, with over 400 refereed papers per year and remaining steady for the past decade; even more impressively, the mean citation rate per Chandra paper is 35 six years after publication;

5. and strong community interest is evidenced by participation in workshops and white papers.

The observatory is committed to enabling science as recommended by the community, including new science observations, theory, and archival research. For example, during the last Cycle, a total of 28 theory and archival proposals were accepted, with over $1.7M in funding distributed to the community.

That said, the panel encourages the project to investigate efficiency savings through evaluation of both science and mission operations. For the former, consideration of the number of FTEs and responsibilities for activities not related to mission operations is appropriate. For the latter, evaluation of lights-out weekend activities is appears to be the correct choice.

The 2014 SR panel found "Much of the data reduction and analysis software is custom-built for Chandra data. While the Panel is confident that there are no significant technical challenges to a prolonged lifetime, in the unlikely event of a failure on the observatory, the Chandra Project needs to have a plan to ensure an orderly transfer of the relevant information to the High Energy Astrophysics Science Archive Research Center (HEASARC)." The CXO project discussed this point with the 2016 SR Panel that the project is considering how to begin preparing such a plan. The SR panel noticed that the project interpreted the 2014 finding to mean that they need to prepare now an executable plan to complete and closeout the final archive. The panel believes this is not warranted at this time but the project does need to look ahead and write down their concepts for completing the archive. This is an important undertaking to do at this time and should be relativity easy task to complete. The Mission Archive Plans ( see http:// …. nasa.gov) prepared by the missions of NASA's Heliophysics Division and submitted to the Heliophysics Senior Review panels is an appropriate example of a concept paper that the CXO project might want to consider. The panel believes that if that CXO project prepares and submits a MAP to their next Senior Review, this would satisfy the finding from the 2014 SR.

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

The 2014 SR panel found "We endorse the concept that to reduce cost, operations and the ground system should be examined by senior engineers from other NASA projects for new ideas that may result in cost efficiencies (we reiterate the findings of the 2012 and 2010 Senior Review Panels)."

In May 2015, the CXC convened a panel of six experts representing a broad cross section of NASA mission operations activities. [Note that science operations were not under the purview of this panel.] The operations review panel was extremely complimentary to the Chandra operations, noting their excellent job maximizing the Chandra science return while being excellent custodians of the spacecraft. The panel of experts found no quick fixes or "low-hanging fruit" to increase cost efficiencies. The panel's report contains several findings intended for the CXO project to investigate and implement as appropriate.

During the SR site visit, we were given a briefing on how the project was responding to the operations panel report. The SR review panel finds that the CXO project is taking the correct responses and will make appropriate adjustments to their procedures and operations configurations. An example of one of these adjustments is that CXC had experimented with making two-week observing plans, but found that nearly 100% of schedules required being redone at least once. The CXC has now returned to one-week observing plans. As another example, the project is carefully managing expertise, cross-training, and software development to ensure that operations continues with the same level of support, deemed necessary to maintain a high level of observing efficiency.

Nevertheless, one expert member of the SR panel noted concern that the CXO project suite of software procedures for interacting with the observatory is antique, and is cumbersome and expensive to operate and maintain. The panel complements the project as it continues to investigate operations tools and procedures employed at other NASA-sponsored operations control centers, with the goal of streamlining CXC operations.

Of special interest to the SR 2016 panel was the issue of the deterioration of the MLI and the associated increased heat load to the spacecraft and instrument subsystems. This problem is well known and has the attention of NASA management as well as the CXO user community. The panel received several briefings on how the increased heating is being managed via a number of methods, primarily through sequencing of science targets so as to balance satellite heating and cooling, and making four CCD observations with ACIS the new standard rather than the six which were standard earlier in the mission. In the future, limiting most observations to three CCD's will likely become necessary. While pointing constraints are in place and are getting more restricted, the SR panel agrees with the project that current mitigation steps are permitting the CXO's full science program, with all approved observing programs performed.

The project briefed the panel on steps and studies they are conducting to forecast the increasing heat load to observatory subsystems over the next decade. These studies show that CXO should be able to successfully conduct its approved science programs for at least the next five years using the current mitigation strategies, with little change in science efficiency expected. The CXO project will continue to the monitor the heating problem and impacts to the subsystems and observing programs; if the situation worsens, NASA management and the observing community will be informed. The heating issue could the limiting technical constraint to the lifetime of the observatory. Future SR panels will evaluate the expected time scale that on which threshold is expected.

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

The stewardship of the observatory remains exemplary. The Project's highest priorities are to maximize the scientific return of the observatory while maintaining the health and safety of the instruments and spacecraft. The Project’s staff members 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 a more than 40% reduction in FTE since 2002.

The operations team has maintained a highly efficient scheduling of the telescope, with allowances for target of opportunity and director's discretionary programs, which is well-balanced with risk mitigation for the deteriorating thermal regulation of the telescope. The operations team has done a commendable job in tracking and projecting the thermal hazards that affect the health of the observatory, and making appropriate adjustments to the scheduling and operations to prolong the health of the facility.

While Chandra has had to make several cost-cutting efforts that challenge the balance of efficiency with high-quality scientific return, the Project clearly sees its grants program (including the general investigator program) as a protected resource, and has worked to see that it retains the same level of funding. This is good, as there is a perceived "funding-floor" in the timely dissemination of important results. Flat or stagnant GO funding, without modest accommodations for inflation, will necessarily reduce the overall scientific return.

The science allocation process through the annual CXC peer reviews remains highly effective in maximizing the breadth of astrophysical science addressed by Chandra. The oversubscription rate is healthily high, and insures strong science is executed. The directorate values a proposal-driven process for determining the science directives of the observatory. This strategy appears to be working well, and there are no obvious deficiencies in the allocations to any specific science area, or proposal size. Continued reevaluation of these allocations, weighing them against publication productivity metrics, is an important task for the project to maintain.

The success rates for female PIs has been essentially equivalent to those for male PIs over the Chandra lifetime, which seems better than most other observatories. The panel feels that is important to ensure that the reward fractions are commensurate with representation in the community, and to reduce factors for unconscious bias in the science review process. Steps to this end made by the CXC in concert with other NASA facilities and the community as a whole are important

The SRP supports the team’s careful and conservative approach to mitigation of the contamination in the ACIS blocking filter. We concur that it is important for the team to continue data collection, including assessment of the impact on observing efficiency through community surveys and the peer review process, and to involve the CUC and the community in the process where feasible.

The Chandra team has developed a work-around to compensate for the loss of the EPHIN radiation monitor that had been used to safe the instruments during times of high particle fluences. Flight software was changed to use the HRC anticoincidence subsystem to turn off the instruments. Returning to

operation after a radiation event is now based upon data from the GOES satellites indicating the high radiation environment had abated. This procedure was based upon Chandra studies of the correlation of the GOES data with that of the HRC anticoincidence system before the failure of the EPHIN instrument.

As a result of the failure of one thruster and concerns for a second one, the Chandra flight software team has developed new software to permit operating an arbitrary combination of thrusters chosen from among the two thruster banks.

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

1. *Productivity and Impact:* The panel finds that Chandra continues to be a highly productive observatory with high impact on most of the science fields identified in the 2010 Decadal Survey, and the NASA/SMD Science Plan and Roadmap. **See Section 2**

2. *Stewardship*: The Chandra team has met the Goals set out in the three PMOs to continue its excellence in stewardship of the Chandra observatory, timely distribution of well-calibrated data to users, and maintenance of the Chandra archive. This excellence is profound in the face of an aging spacecraft and instruments. **See Sections 1,2**

3. *Enabling Science:* The success in enabling science is well documented by the number of high-impact discoveries announced during the 2014-2016 time frame, the continuing high yield of papers per observation and exposure time, and the roughly constant rate of oversubscription of the time awarded in the peer review process. **See Section 2**

4. *Publications and Proprietary Period:* The median time from observation to publication of approximately 2.4 years suggests that the nominal GO grant duration of 1-2 years and the proprietary period of 1 year are still appropriate at this point in the mission. **See Section 2**

5. *Community Engagement:* The Chandra team has engaged the CUC and the broader scientific community through regular workshops in an assessment of the scientific footprint of the observatory and to establish the key science questions the observatory should be addressing. **See Section 2**

6. *Software Development and Calibration:* The Chandra team continues to provide software and calibration upgrades at the rate necessary to enable prompt reduction and analysis. The panel concludes that ongoing work on software development and calibration addresses the needs identified by the community through the CUC and help desk and in previous Senior Reviews. **See Section 2**

7. *Publication Metrics:* The panel commends the Chandra team for collecting detailed metrics and finely granulated publication data. **See Section 2**

8. *Reduction of Operations Budget*: Since launch, the Observatory has significantly reduced the operations budget, as expected for a mission in its extended operations phase. **See Section 3**

9. *Transfer of Archive to HEASARC:* The panel believes that a detailed plan for the transfer of the Chandra data archive to the NASA HEASARC is not warranted at this time but the project does need to look ahead and record their concepts for completing the archive. **See Section 3**

10. *Response to Operations Review:* The SR review panel finds that the CXO project is taking the correct responses and will make appropriate adjustments to their procedures and operations configurations. **See Section 4**

11. *Cross-training:* The cross-training of and multi-tasking by very capable people, along with the development of effective monitoring tools, has mitigated the disadvantages of a more than 40% reduction in FTE since 2002. **See Section 5**

12. *Release of Second Chandra Source Catalog:* The continued development of the Chandra X-ray Source Catalog with future observations will provide the scientific community with a powerful tool for enhanced scientific return. **See Section 1**

13. *The establishment in Cycle 18 of the Joint Large Proposal Program (JLPs)*: The Joint Contingent Large Project proposal opportunity is a strong beginning to promote large multi-wavelength observational campaigns. **See Section 1**

14. *Reallocation of time for Large Programs*: The CXC team discontinued the X-ray Visionary Programs (XVPs) and increased the minimum amount of time required for Large Programs from 300ks to 400ks. We believe it is important for the Director to continue assessing the effectiveness of the peer review structure and adjust upcoming calls for proposals based on that assessment in consultation with the CUC and input from the community. [SH] **See Section 1**

15. *Seamless continuation of the CXO observing program despite age-related degradation issues:* The SRC highly commends the stewardship of the CXC in avoiding losses of observing time by effective mitigation of multiple issues. **S**ee **Section 4**

16. *Mitigation of Aging Effects*: The Chandra team has done an outstanding job of monitoring and preserving the health and safety of the observatory under the challenges posed by an ageing spacecraft. **See Section 2,4**

17. *Efficient Scheduling:* The operations team has maintained a highly efficient scheduling of the telescope, with allowances for target of opportunity and director's discretionary programs,

which is well balanced with risk mitigation for the deteriorating thermal regulation of the telescope. **See Section 5**

18. *Maximizing the breadth of astrophysical science*: The science allocation process through the annual CXC reviews remains highly effective in maximizing the breadth of astrophysical science addressed by Chandra. **See Section 5**

*19. Diversity:* The success rates for female PIs has been essentially equivalent to those for male PIs over the Chanda lifetime. **See Section 5**

20. *EPHIN Radiation Monitor:* The Chandra team has developed a work-around to compensate for the loss of the EPHIN radiation monitor that had been used to safe the instruments during times of high particle fluences. **See Section 5**

21. *Mitigation of Thruster Loss:* The Chandra flight software team revised the thruster control software to permit operating an arbitrary combination of thrusters chosen from among the two thruster banks. **See Section 5**

22. *Science Enhancements via Proposal Option Adjustments:* The Chandra team is constantly revising the proposal options available to the science community in response to their analysis of proposal findings, such as the separation of galaxies and galaxy clusters into separate peer review panels. This adjustment enhanced the proposal successes for galaxy observations that had been identified as a disadvantage when competing with galaxy clusters. **See Section 1**

23. *Advanced Observatory Simulator:* The Chandra team has met the challenges of maintaining an aging but highly advanced simulator system which is used for anomaly investigations, engineer training, development of responses to potential anomalies, and testing of flight software changes.

24. *GO budget:* The panel believes that GO budget is falling behind with inflation and needs to be increased. There should be ways to increase this budget to insure continued high scientific output. **See Section 1,5**

25. *GTO Time*: While recognizing the essential expertise and experience provided by the Instrument Teams for maintaining a highly productive and well calibrated observatory, we reiterate the concerns of the 2010, 2012 and 2014 Senior Review panels regarding the continuing allocation of 2.45 Ms/yr of GTO time, now more than 15 years after launch. **See Section 1**

26. The PMOs were somewhat generically defined and not specific to Chandra; in future reviews, the inclusion of PMOs written with specific metrics to measure success could serve as a useful tool for strategic planning of the Observatory. **See Section 1.**