2014 Senior Review of the Chandra X-ray Observatory

March 24-27, 2014

Panel Members:

Dennis Ebbets	**(Ball Aerospace & Technologies Corp.)**
Charles P. Holmes	**(NASA Headquarters, retired)**
Dan McCammon	**(University of Wisconsin)**
H. Richard Miller	**(Georgia State University)**
Richard Mushotzky	**(University of Maryland)**
I. Neill Reid	**(Space Telescope Science Institute)**
Edward Sion	**(Villanova University)**
Ann E. Wehrle	**(Panel Chair; Space Science Institute)**

Executive Summary

Chandra X-ray Observatory (CXO) is one of NASA's Great Observatories. It has a large community of users who continue to produce groundbreaking scientific results. Chandra is the most powerful facility for X-Ray astrophysics, and its unique capabilities have no likely successor in the foreseeable future. The science of Chandra addresses themes of Physics of the Cosmos, Cosmic Origins and Exoplanet Exploration that were identified as priorities by the 2010 "New Worlds New Horizons" Decadal Survey, NASA's 2010 Science Plan and are the focus of the Astrophysics Division. The prospects for further compelling science return in the future are excellent. This panel enthusiastically endorses the extension of the Chandra mission.

Some of the most exciting recent results directly connected to the NASA Strategic Plan include observations of phenomena and environments extremely close to black holes, the possible detection of filaments of the Intergalactic Medium feeding into a large cluster of galaxies, detection of sources at very high redshift, and studies of exoplanet systems in X-rays. These results are directly related to the NASA Strategic Plan.

The staff and infrastructure of the Chandra Project are most effective at enabling new science. The observatory staff provides effective tools for proposal support, conducts peer-reviewed selections of new observations and operates the spacecraft effectively with a high degree of efficiency. Data are processed and delivered rapidly. The data archive ensures easy availability and dissemination for future researchers. Powerful software tools facilitate data analysis and presentation. As a result, data from Chandra have a very high rate of publication (~94%) in peer-reviewed scientific literature, and appear in a commendable suite of public engagement activities. Chandra discoveries continue to have an extraordinarily high impact on both the scientific and public understanding of our universe.

There are no technical obstacles to Chandra's continuing scientific productivity. There have been few events or anomalies that cause loss of observing time or data. The health of the 15-year-old observatory is excellent and well understood. The operations staff is proactive and diligent about monitoring, trending, modeling and managing its performance. Degradation of thermal insulation is a concern but its effects have been mitigated by careful observation planning.

Stewardship of the observatory is exemplary. The highest priorities are to maximize the scientific return of the observatory while maintaining the health and safety of the instruments and spacecraft – extending its lifetime as long as possible. The Project's staff members are 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 has mitigated the disadvantages of staff reductions and has contributed to a high retention rate. The individual skill sets and institutional memory at the Chandra X-ray Center (CXC) and its partner organizations have largely been preserved despite more than 40% reduction in FTE since launch.

The Panel makes the following findings that may be useful to enhance future returns from the Observatory:

(1) Chandra has unique capabilities that will not be duplicated or replaced for many years. The Panel commends efforts to expand the "discovery space" available by developing major, focused scientific

projects building upon recent scientific successes. The detailed, enhanced implementation of such "Key Projects" should be developed with additional community input

(2) The GO program is crucial to the scientific productivity of the mission and maintaining funding at least at the current level is essential.

(3) In addition to guidance from experienced senior researchers, the panel is confident that engaging younger scientists in long-range planning would infuse valuable perspectives from people who represent the future of the field.

(4) 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 HEASARC.

(5) 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).

(6) From the information provided to the Panel, we are confident that the Chandra Project can successfully navigate the effects of a flat budget in FY 2015-FY2016. Flat budgets in the extended horizon would present significant challenges.

The general Prioritized Mission Objectives in the proposal were augmented by a sample of future Chandra science projects related to NASA science strategic objectives. The proposal included relevant metrics that enable this and future Senior Reviews to evaluate both the performance of the CXO and the scientific productivity of the mission. Statistics related to proposal submission and acceptance indicate a continued broad interest in Chandra science. Observing efficiency, anomaly resolution and timely delivery of processed data products describe effective use of mission and science operations resources. Publication and citation rates quantify the value and impact of the observatory as perceived by the professional community. Tallies of access to web sites, press releases, educational and public activities track impact beyond the scientific community. Staffing levels show CXO to be within NASA guidelines for extended missions. The Panel commends the project for clear presentation of informative metrics for the 2014 Senior Review Panel and encourages continued tracking for future reviews.

Introduction

The Chandra X-ray Observatory (CXO) is one of NASA's Great Observatories with a large community of users who continue to produce groundbreaking scientific results. It is the most powerful facility for X-Ray astrophysics, and has no likely successor in the foreseeable future. The science of Chandra addresses themes of Physics of the Cosmos, Cosmic Origins and Exoplanet Exploration that were identified as priorities by the 2010 New Worlds New Horizons Decadal Survey, NASA's 2010 Science Plan and are the focus of the Astrophysics Division. The prospects for further compelling science return in the future are excellent. **The panel enthusiastically endorses the extension of the Chandra mission.**

The Chandra Senior Review Panel met on March 24 to 27, 2014 at the Chandra X-Ray Observatory Operations Center in Cambridge, MA. The Chandra Project's Senior Review proposal was provided to the Panel in advance of the Panel's meeting. Following a tour of the observatory facilities and detailed project presentations by Chandra scientific and technical staff, the Senior Review Panel (SRP) met in executive session to prepare its report. The Panel commends the Chandra staff on their hospitality and openness. The CXO proposal was comprehensive and clearly presented at an appropriate level for this review. The staff responded promptly to requests by the panel for additional information.

This Report is structured to match the charge to the Panel as given in the Call for Proposals- Senior Review by Jeffrey Hayes and Debra Wallace of NASA Headquarters (pages 12-13). The following sections of this Report are:

1) Assessing the scientific merit and expected science return of CXO,
2) Alignment with NASA's Strategic Goals,
3) The effectiveness of CXO in enabling new science, archival research and theory,
4) Effectiveness of the science and mission operations processes and technical mission health, and recommendation on mission extension
5) Observatory stewardship and maximizing science quality, observational efficiency, and return on investment,
6) Enhancing the science return and
7) Findings of the Panel.

.

1. Assessing the scientific merit and expected science return of CXO

The Chandra X-ray Observatory has the highest X-ray spatial resolution of any present or planned X-ray observatory. In addition, it has the highest point source X-ray spectral resolution at $E< 2$ keV for the foreseeable future. These unique capabilities allow it to obtain exciting data crucial for understanding a wide variety of cosmic phenomena: from planetary transits to the most distant quasars. As examples, in the last 2 years CXO observations have probed physics on scales ranging from 10 times the event horizon of a black hole to the largest scales of the cosmic web. These observations help to strongly constrain fundamental cosmological parameters and processes responsible for forming and shaping galaxies. The vast breadth of Chandra science reaches almost every area of astrophysics, including star and galaxy formation, the creation of the elements, the origin and evolution of black holes and galaxies and placing stellar activity in a cosmic context.

Recent discoveries with Chandra have broken new and unexpected ground, changing our understanding of the physics of objects in the universe from the largest clusters of galaxies to the smallest neutron stars. In addition Chandra has tremendous synergy with NASA's other Great Observatories (Hubble and Spitzer Space Telescopes) as well as with premier ground-based observatories (NOAO, NRAO, ALMA, Keck, VLT). Chandra will maintain the capability to respond to new discoveries across the electromagnetic spectrum for the foreseeable future. With new facilities like ALMA, JWST and Astro-H coming on-line in the next few years, continued operation of Chandra is crucial for obtaining critically important complementary data. Only Chandra has the angular resolution to be compatible with the new generation of adaptive optics in the near-IR and the sensitivity to properly complement the prime science goals of JWST. As is evident from the recent literature and NASA's Astrophysics Division goals, a highly sensitive X-ray mission is vital to the health of the entire astronomical enterprise. This is demonstrated by the very broad range of science programs and Guest Observers who propose to Chandra.

Many of the notable recent discoveries have received significant allocations of observatory time. These discoveries can be significantly enhanced and extended through the investment of future observations. These activities will guarantee that Chandra will be scientifically very productive over the next decade. Chandra's unique capabilities will be crucial for interpreting the results from present and future astronomical observatories.

For example, wider and deeper follow-up campaigns to the Chandra deep fields will allow strong constraints to be placed on the formation epoch of supermassive black holes and the nature of the first black hole seeds. The high angular resolution of Chandra allows the stacking of X-ray data on the positions of very high redshift galaxies discovered in the Hubble Ultradeep Field and the Frontier Fields. Already, preliminary results indicate that the growth of supermassive black holes must change strongly with redshift.

Understanding the nature and evolution of the intergalactic medium, the repository of most of the baryons in the universe, was highlighted as a prime goal by the 2010 Decadal Survey "New Worlds, New Horizons in Astronomy and Astrophysics". The unique Chandra capability of high spectral resolution at low energies has allowed the most robust measurements of the temperature and density of the $z<0.4$ intergalactic medium along one line of sight. Deeper observations of this target will significantly increase the signal to noise and allow the development of other targets for this area of science.

Chandra results on the masses of 28 clusters combined with cosmic microwave background and baryon acoustic oscillation results have produced the tightest available constraints on the agreement of cosmological observations with general relativity and the precision measurement of cosmological parameters. A much larger sample of clusters can be obtained in the next few years to sharpen these constraints even more. These same cluster data provide amongst the best constraints on the nature of dark matter by severely limiting the cross-section of interaction of dark matter with both itself and baryons.

The formation and evolution of large scale structure (galaxies and clusters of galaxies) remains a major problem in general astrophysics. There are strong indications from detailed theoretical work of the crucial importance of active galaxies in these processes – the so-called feedback processes. Chandra observations of feedback in clusters of galaxies are the best direct observations of this phenomenon and have shown that the power required to produce the observed feedback can be equivalent to almost the entire energy output of a supermassive black hole. Recent results have shown the nature of feedback changes over redshifts from z=1 to the present epoch.

As highlighted in the 2010 Decadal Survey, the formation of high mass stars is crucial for our understanding of the formation of the elements and the ecology of the interstellar medium. Recent Chandra observations have shown that massive stars can form in two independent ways, challenging simple models of their origin.

The physics of what happens close to a black hole is one of the main science drivers of modern astrophysics. Two recent Chandra results have been able to locate the origin of X-ray emission within 20 times the event horizon of a z=0.6 active galactic nucleus via observations of gravitational lensing of the X-ray emission, an observation possible only with Chandra More extensive Chandra observations of other lensed active galactic nucleus at even higher redshifts will enhance and extend this ground-breaking result. Observations of the very low-efficiency accretion occurring around our galactic center and a nearby non-active supermassive black hole in the galaxy NGC3115 show that the flow is a complex mixture of inflowing and outflowing zones.

The scientific productivity of Chandra is demonstrated by the very high oversubscription rate (~5.5 in 2014) for new observations, the high publication rate (~440 refereed papers/year in 2012 and 2013), the high publication citation rate (30 citations per paper after 6 years), and the extensive use of the data archive and related CIAO software (~10% of the data archive contents are downloaded every month; more than 1000 CIAO software package downloads per year). Over 284 PhD theses worldwide have used Chandra data. The accepted proposals to date include 3630 individual PI's and Co-I's, including ~192 new investigators per year. The total number of investigators is a large fraction of the total worldwide astronomical community.

2. Alignment with NASA's Strategic Goals

The Chandra X-ray Observatory is an integral and vital part of the NASA Astrophysics Division portfolio, directly addressing key scientific objectives articulated in the 2010 Decadal Survey, "New Worlds, New Horizons in Astronomy and Astrophysics". Chandra is crucial to investigating the development and growth of super-massive black holes in the early universe, mapping the distribution of hot gas in the intergalactic medium and probing material near the event horizon of black holes. These issues lie at the core of "Revealing the Extremes of Nature", a central theme of the 2013 Astrophysics Roadmap, "Enduring Quests, Daring Visions". Chandra addresses all three primary fields within the NASA Astrophysics Division: Exoplanet Exploration, Cosmic Origins, and the Physics of the Cosmos, with examples of recent highlights and anticipated future science projects clearly delineated in Tables ES-1 and ES-2 of the CXO proposal to the 2014 Senior Review.

3. The effectiveness of CXO in enabling new science, archival research and theory

The large number of Chandra proposals (636 in Cycle 16 in March 2014) indicates a very high demand for observing time, archival research and theoretical studies. Many proposals investigate new ideas that were not even imagined before launch. Many exciting results published in refereed journals are released to the public as press releases (~30 per year) with excellent illustrations that have high visibility in the media. Proposal categories have evolved to address changes, specifically to accommodate large proposals for major, coherent projects that address key questions in astrophysics that require large amounts of observing time ("X-ray Visionary Projects"). The CXC has facilitated cooperation with other observatories, both space- and ground-based. The CXC staff work with PI's who have constrained observations (e.g., observing a binary star at a certain orbital phase, or coordinated multiwavelength observations with several other observatories); such observations comprise about one-third of all Chandra observations.

The CXC has developed an efficient, flexible, and easy to use data analysis suite "CIAO" that makes it straightforward for both novice and expert users to take full scientific advantage of CXO data. Budget restrictions have limited the range of platforms that can be supported, but almost all users have access. We commend the CXC efforts to take advantage of international interoperability standards to provide new tools for correlating Chandra results with other data bases. We note that a large fraction of current papers are making use of archival data, and that the usefulness of the data appears independent of their age (for details and statistics, see Section 1 of this report). The tools they have developed for accessing archival data are both easy to use and powerful, with over 10% of the archive downloaded every month. These tools will help maximize long-term benefits of the archive.

A new version of the Chandra Source Catalog will include data on 107,000 sources, three times as many sources as the original catalog. The data-mining interface, known as CSCview, accesses source properties and source-based data products such as images, spectra, light-curves, and instrument responses.

The theory program embedded within the CXO Call for Proposals remains a small (eight accepted proposals in Cycle 15) but vital aspect of Chandra's scientific mission since it provides the requisite framework for modeling and interpreting X-ray observations in support of the CXO science objectives.

4. Effectiveness of the science and mission operations processes and technical mission health; recommendation on mission extension

In summary, the science and mission processes are highly effective. There are no technical obstacles to continuing the ground-breaking science and high productivity of the mission. **We enthusiastically endorse the recommendations for extension of the Chandra mission.** The following subsections detail the science and mission operations processes and technical mission health.

4.1 Science Operations Processes

CXC scientific staff support mission operations, calibrating and operating the instruments, planning observations, and assisting the scientific community. These processes are smooth running and efficient as befits a mature Great Observatory. The fact that the staff are actively pursuing research means that they are fully invested in pushing the limits of the observatory and instruments. The Operations Science Support team has developed the mission planning tool that helps maintain acceptable instrument temperatures in the face of degrading thermal insulation.. The Calibration team ensures that the calibration programs will maintain the accuracy required for precise scientific results. The Science Mission Planning team designs schedules that achieve an observing efficiency of ~75% which is about the maximum possible given the observatory's orbital constraints. The Science Data Systems Planning group develops specifications and algorithms for data processing and analysis software.

Science Data Systems groups support the Chandra science observations from proposal through pipeline processing to data delivery and archive. The proposal tools are easily accessible. The Chandra Interactive Analysis of Observations (CIAO) software is widely used, flexible enough for both novice and expert users. Observers typically receive data within 30 hours of observation, following verification and validation by a staff scientist. Production of pipeline data using the current calibration database appears to be smooth. The archive interface design is excellent, and data delivery from the archive is a matter of minutes. The 4-year cycle for hardware replenishment appears to be working well.

The Instrument PIs and their teams provide essential expertise. As Guaranteed Time Observers, they push the envelope of instrument capability. Their refereed papers are cited at comparable rates to General Observer papers. We note that NASA Headquarters has allocated 2.45 Ms/year to the GTO program. We believe that the allocation should be re-examined as the mission progresses, in agreement with the previous Senior Review in 2012.

Science community support covers a broad range of activities. The Chandra Director's Office oversees services to the community. We find that they ensure a very high level of support.

The grants program is efficient and well run, with grants quickly issued to both PIs and Co-I's to maximize use of the $11M in grant funding (and to avoid double overhead charges). A 6% reduction in the funding was partly restored following the 2012 Senior Review recommendation. This SRP is concerned that the buying power of grants, which have been constant in dollar terms, has been eroded by inflation over the fifteen years since launch. Namely, a $50K grant today is needed to buy what a $35K grant bought in 1999, according to the US Department of Labor, therefore the present level of GO grants only supports 70% of the efforts that it did in 1999.

The Director's Discretionary Time program accommodates Target of Opportunity observations and other unique observing opportunities. The Chandra User Committee provides representation of the scientific community to the Project to assess CXC activities and advise the Director.

The Chandra website accommodates both the scientific community and the public. It's easy to find information and get questions answered promptly through the Help Desk. Complex questions have a rapid turnaround time.

We note that public communication is a vital part of scientific discovery, and we commend the Chandra Project staff on their award-winning efforts. We hope that NASA will issue guidance soon that recognizes the important role played by public engagement and communication.

4.2 Mission Operations Processes

The observatory is operated by a set of teams who organize the science operations plans, the detailed mission operations plans and conduct the on-console daily operations. These teams are supported by an engineering staff that constructs the day-to-day analyses of the performance of the spacecraft systems as well as maintain the on-orbit systems. The online operations team operates two 9.5-hour shifts per day, 7 days per week, to cover the 3-pass-per-day schedule of spacecraft contacts via the Deep Space Network. To ensure error-free operations and to support complex commanding activities, two operators are on console for each pass. Operators also develop and test procedures, verify ground system software modifications, and participate in training and operations simulations.

The several aspects of mission planning, engineering and operations are well-defined, appropriately integrated with members of staff fulfilling multiple roles, and are running quite smoothly.

In July 2013 the Chandra Project successfully completed its second major upgrade of the Operations Control Center Data System (OCCDS) since launch. The upgrade includes new servers and workstations, new network equipment, an updated operating system, migration to an open-source database from a vendor-orphaned database, and transition to a single server platform hosting virtualized, formerly separate, servers. The OCCDS is comprised of hardware and software for real-time spacecraft contacts, mission planning, command load generation, and engineering analysis. The OCCDS contains a database of over 30,000 command definitions, telemetry measurement definitions and other data elements, and a distribution subsystem that connects the Operations Control Center to the DSN and other external systems. Database telemetry limits are updated annually or as needed. The OCCDS contains ~3.6 million lines of source code, 44 computers and 13 network devices. All software is under configuration management, with changes controlled through established configuration control boards.

The SRP notes that the OCCDS evolved from that system delivered from MSFC in the mid-1990s. NASA’s fleet of robotic spacecraft launched after Chandra have undergone a major evolution in the design and implementation of their ground systems. Some techniques may benefit Chandra operations if they can be incorporated in a cost-effective manner. The project stated that their previous studies for lowering operations “showed that the cost and time needed to develop the necessary software and procedures exceeded existing program resources.” The SRP believes that the issue should be re-opened with the goal of developing a plan for lowering operational costs that could provide a significant return on investment for redirecting resources within the project and/or future savings.

4.3 Information Technology Security

The Chandra Project works closely with NASA’s Information Technology security officials to ensure that Chandra’s Information Technology security practices and procedures meet or exceed Federal standards. This is a significant effort that has increased as NASA Information Technology security requirements evolve.

4.4 Technical Mission Health

The SRP finds the spacecraft and scientific instruments to be in excellent condition. The Observatory has experienced very few anomalies since launch. Chandra remains fully single-fault tolerant without loss of scientific capability.

The Chandra X-ray Observatory carries a high resolution mirror assembly (HRMA), two imaging detectors (ACIS, HRC), and two sets of transmission gratings for high resolution spectroscopy (HETG, LETG). Important Chandra features are: sub-arcsecond spatial resolution, sensitivity to soft X-rays up to 10 keV, and the capability for high spectral resolution observations over most of this range. Chandra has been operating in space for nearly 15 years and the observatory transits Earth’s radiation belts every 2.7 days. Chandra’s highly eccentric orbit makes possible continuous observations of up to ~185 ks. The achieved observing efficiency continues to be maintained at ~75% of total orbit time and is limited primarily by the need to protect the instruments from particles, especially protons, during passages into the Earth’s radiation belts.

The effects on scientific return from the expected gradual degradation of some of the observatory's subsystems have been minimal. The observatory team proactively monitors these degradations and has adapted the operations appropriately. Accumulation of these effects over time has increased the flight and science teams' workload.

The most notable technical issue on the spacecraft is that the spacecraft's multi-layer insulation and other thermal protective surfaces have degraded during the mission due to solar particles and UV radiation, resulting in elevated temperatures. The effects of the degradation have reduced the ability to provide uninterrupted, extended observing time at particular spacecraft orientations. Mitigating the effects has increased the complexity of mission planning. Temperatures are now managed using mission planning constraints that limit observations around the anti-Sun direction.

The aspect camera, ACIS electronics, and the propulsion tanks all now require thermal management. An innovative new modeling infrastructure has significantly reduced the effort required to predict thermal behavior, and well calibrated models for each of these units are now in place. Further increases to the temperature limits on the fuel tank or the ACIS electronics will require extensive study and may not be feasible without accepting some additional mission risk. Keeping the ACIS electronics and the propulsion tanks within defined limits does not currently impair scheduling capability or science efficiency; however, with further degradation these constraints will likely begin to dominate the long-term observing schedule and may eventually impact the observing efficiency.

To maintain its pointing, Chandra has two gyroscope packages, each containing two rotors. Nominal operation uses one gyroscope package at a time. Chandra currently uses the alternate gyro package, leaving the original unit in reserve. The reserve gyro package has performed flawlessly when used twice during safe mode events. Chandra could readily be operated with one rotor from each gyroscope package without science impact, and ground procedures and software products have been created to swap this configuration if needed. Chandra could even operate with only one rotor and the fine sun sensor (FSS) with minimal science impact; however, developing the necessary flight software and ground processing algorithms would require extensive effort.

4.5 Spacecraft Events since last Senior Review

The Chandra proposal noted two spacecraft events that required configuration changes with implications for safing. The strategies have been effective. The primary-side Fine Sun Sensor (FSS-A) showed problems and was swapped for the alternate-side FSS-B in May 2013. FSS-A was configured for use in safing to maintain a high level of redundancy. In early 2013, one of the four thrusters used for unloading angular momentum showed decreased thrust. The system was swapped to the B side for normal operations, with the failed B-side thruster not used and the A-side thrusters reserved for safing. With the new thruster configuration, Chandra has full safing capability and can adequately manage momentum for nominal operations. Planning momentum unloads using three thrusters requires extra effort, but does not impact observing capability or science efficiency. The operations team is investigating methods to allow using thrusters from both banks in the event of future failures.

4.6 Expected Lifetime

Chandra recently commissioned a study from the spacecraft builder who examined these trends and reported the expectation that the spacecraft should be sufficiently serviceable for the Chandra science operations for the next 10 years.

4.7 Status of Mirror Assembly and Instruments

HRMA: On-going calibration of the HRMA shows that its performance has been extremely stable, with no observable change in Chandra's end-to-end imaging capabilities since launch. For the foreseeable future, Chandra will continue to be the best imaging X-ray telescope ever launched.

ACIS: ACIS continues to perform superbly, with all ten detector chips functioning well. Chandra's evolving thermal environment has led to a limitation on the number of simultaneously operating chips for some observations. The ACIS instrument's low-energy detection efficiency has decreased gradually due to a buildup of contamination on the ACIS optical blocking filter. The project estimates that in five years the gradually decreasing transmission will still be better than the original project requirements. During the first months of the mission, the ACIS front-illuminated chips incurred a significant increase in charge transfer inefficiency (CTI) due to damage by low-energy protons scattered by the Chandra mirrors. The CCDs have also experienced an expected small increase in CTI due to particle impacts during observations. The main consequence is the need for continued calibration of gain versus time and position on the CCD. The current rate of CTI increase, about 2% per year, is well within budget for at least 50 years of operation.

HRC: HRC continues to operate with performance nearly unchanged since launch. Increased understanding of the imaging behavior gained with on-orbit experience has led to better images. Long-term trending and analysis of HRC data shows no limit violations or significant problems.

HETG and LETG: The HETG and LETG are inserted into the beam for dispersive spectroscopic observations. On-going calibrations show no change in their performance, and they continue to work properly.

5. Observatory stewardship and maximizing science quality, observational efficiency and return on investment

We commend the Chandra project staff for their demonstrated care and thoughtfulness in observatory stewardship with the primary goal of keeping the science return from mission operations as high as possible via maintaining the viability of the spacecraft and data systems. They have thought carefully about potential future spacecraft problems and are developing procedures and training to rapidly and efficiently handle a wide variety of potential issues.

There have been relatively few new hires to the observatory staff in recent years, creating a lean organization and offering limited career paths to those who remain. Nonetheless, cross-training has proven an effective means of broadening staff skill sets and maintaining enthusiasm. We believe that the observatory is in excellent hands, with the current level of staffing. The Chandra team has developed a system that allows a very high observing efficiency consistent with the physical limits from radiation belt passages, building on their 15 years experience of successful mission operations.. The very low level of safing events may be due in large degree to their operations procedures.

The Chandra grants program is vital to the scientific success of the mission and we strongly encourage the Chandra mission to explore ways of maintaining the effectiveness of the grants program in the light of budget constraints. Both the GTO teams and GO community have continued to be highly productive producing numerous and highly cited publications. The median time from data release to first publication is a rapid 2.5 years and 96% of all observations result in at least one publication after 8 years. Sixty percent of Chandra data are published in three or more papers after eight years.

We commend the CXC for its efforts to make access to the data as easy as possible and allowing both naïve and expert users to efficiently analyze the data. We were shown new analysis procedures which have the potential to significantly simplify the analysis tasks for new data and to vastly increase the usefulness of the vast Chandra archive. However the CXO software and mission operations system are unique, and thus the potential for significant reductions in costs due to redundancies and synergies between missions is not available to the CXC.

The Panel had serious concerns that a flat budget profile would impact CXC's ability to fully support the Chandra user community and maximize the science return from the mission. The Panel encourages NASA HQ to examine means of mitigating the effect in future years, and the Chandra administration to explore all possible means of maintaining expertise in key areas. Chandra is a complex system, and we encourage CXO to examine carefully the future balance between operations, mission planning, scheduling and user support.

6. Enhancing the science return

CXO is a mature observatory. Recent programs have highlighted its ability to probe fundamental scientific questions through deep, focused programs that expand "discovery space": probing filamentary structure in the intergalactic medium in observations of the galaxy cluster Abell 133; constraining dark energy through measurements the mass and gas fraction of galaxy clusters; and monitoring time-delays in the lensed QSO RX J1131-1231 to characterize the spin of super-massive black holes at moderate redshift. The Panel encourages CXO to be proactive in supporting further observations of this type, working to highlight key science areas for future study with a community advisory council, through consultations with recent Einstein Fellows and/or solicitation of white papers.

Regular GO and GTO observations continue to be the core of Chandra's science program and an appropriate balance needs to be set in the time allocation process. The Panel believes it will be important for CXO to explore additional mechanisms for devoting a fraction of the available observing time to high (science) risk/high return projects.

The Panel recognizes the clear importance of communicating Chandra's scientific results beyond the scientific community. The CXC staff members are to be commended for the extraordinary innovative methods and techniques they have employed in publicizing Chandra science and engaging the broader public.

7. The Panel's Findings

The Panel makes the following findings that may be useful to enhance future returns from the Observatory:

(1) Chandra has unique capabilities that will not be duplicated or replaced for many years. The panel commends efforts to expand the "discovery space" available by developing major, focused scientific projects building upon recent scientific successes. The detailed, enhanced implementation of such "Key Projects" should be developed with additional community input.
(2) The GO program is crucial to the scientific productivity of the mission and maintaining funding at least at the current level is essential.
(3) In addition to guidance from experienced senior researchers, the panel is confident that engaging younger scientists (for example, the Chandra Fellows of 2000-2005) in long-range planning would infuse valuable perspectives from people who represent the future of the field.
(4) Much of the data reduction and analysis software is custom-built for Chandra data. The Panel is confident that there are no significant technical challenges to a prolonged lifetime of the observatory. However, 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 HEASARC.
(5) We endorse the concept that to reduce cost, Chandra 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).
(6) From the information provided to the Panel, we are confident that the Chandra Project can successfully navigate the effects of a flat budget in FY 2015-FY2016. Flat budgets in the extended horizon would present significant challenges.

.