Issue 35 – Summer 2024

Chandra News

25 Years Later

Celebrating Our Silver Anniversary

Also Inside:

Chandra Source Catalog 2.1 — A Tour of the CXC Data Systems — The Chandra Legacy Program

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The Chandra Newsletter is edited by Thomas Connor, with editorial assistance and layout by Tara Gokas. We welcome contributions from readers. Comments on the newsletter should be sent to: chandranews@cfa.harvard.edu.

Update from the Director

Pat Slane

Merging neutron stars. Once more, I find myself thinking about these energetic events, which represent the prominent formation channel for the highly conductive metal that ceremoniously marks twenty-five years. So, many thanks to our friend GW170817—or, actually, to some more nearby cousin from the past—for helping to seed the celebration of our silver anniversary!

Observing the emission from that first gravitational wave source with an electromagnetic counterpart—detecting the fading glow of the hypernova long after other telescopes had lost sight—is just one of the vast number of *Chandra*'s spectacular contributions to modern astrophysics. From resolving the hazy X-ray background into a speckled array dominated primarily by black holes to peering through a gravitational lens to peek at supermassive black hole formation at the edge of time, *Chandra* has continued to do things that no other X-ray observatory can. It is unique, it is powerful, and it is healthy—and it is poised to help continue framing the future of high energy astrophysics for years to come.

The vast discovery space opened by *Chandra* over the course of twenty-five years is too broad to touch on here, but will be at the core of the 25 Years of Science with *Chandra* Symposium here in Boston this December. Registration and abstract submission are currently open, and you can read more about the symposium in this issue.

Meanwhile, this past year has seen an incredible burst of new and exciting progress with *Chandra*. Following the resolution of an anomaly and the development of a new operations concept for the HRC early last year, the instrument has carried out over 200 new observing segments. The implementation of processes to enable ACIS to provide radiation-level monitoring for detection of elevated solar particle levels—and subsequent safing of instruments—has performed flawlessly. *Chandra* images graced everything from the Metro in Washington, DC, to Sphere in Las Vegas. The release of a call for whitepapers on topics for a *Chandra* Legacy Program resulted in an oversubscription factor of 15, leading to selected programs to study the baryon cycle in nearby galaxies and the detailed structure of a galaxy cluster. And investigations of the *Chandra* Momentum Unloading Propulsion System have resulted in upcoming relaxation of temperature limits that will bring uninterrupted observing times to 2019 levels over a considerable range of pitch angles. In short, every aspect of the mission has continued successfully, with improvements in multiple areas.

Of course, such successes and innovations are not unique to the past year. The *Chandra* team and the broader *Chandra* community have demonstrated a history of unwavering performance over the entire twenty-five years of operation. As nearly everyone reading this Newsletter understands, it was thus completely unanticipated when, last fall, NASA decided to target *Chandra* for very significant budget reductions. The details of this process have been discussed broadly elsewhere, with significant concern expressed by the community and summarized by the *Chandra* Users' Committee. The mission, along with *Hubble*, was directed to go through an "Operating Paradigm Change Review" to investigate potential models for reduced modes of operation at lower cost levels. The results of that process—which included scenarios for a lower-cost *Chandra* mission with drastically reduced capabilities—are still unfolding at the time of this writing. We remain anxiously hopeful for the continuation of this Great Observatory at full capabilities.

A total solar eclipse, viewing the shimmering Aurora Borealis, my first Bruce Springsteen concert—all literally unforgettable experiences. But the nighttime launch of STS-93 to deliver *Chandra* to orbit twenty-five years ago? A life-changing vision for me—and some of you—and the beginning of a revolution in high energy astrophysics.

See you in Boston in December!

25 Images to Celebrate *Chandra*'s 25th Anniversary

In commemoration of the 25th anniversary of the launch of Chandra, we released twenty-five new images highlighting the breadth of Chandra science. You can find a sampling of these images throughout this Newsletter. For Individual object files and more information, see:

https://chandra.harvard.edu/photo/2024/25th/more.html

Chandra Legacy Program

Rodolfo Montez Jr.

In November 2023 the CXC issued the *Chandra* Legacy Program (CLP) call for white papers to identify science challenges for which the capabilities of *Chandra* are absolutely required. These science programs were to be designed to address fundamental questions about our current understanding of the components and evolution of the Universe.

The community of *Chandra* users submitted twenty-two white papers, covering a broad range of scientific topics spanning nearby stellar nurseries to distant galaxy clusters. The white papers honed in on some of *Chandra*'s unique capabilities—from low-background, high-resolution imaging to high-resolution grating spectroscopy—and demonstrated how those capabilities were well-suited to expand our understanding of the Universe.

A committee of seven external (non-CXC) members of the astrophysics community had the difficult task of reviewing the twenty-two white papers over a week-long review. After the CLP Review Committee completed its evaluation of the white papers, recommendations for major science themes were presented and became the following two initiatives for a Call for Legacy Proposals:

Initiative I: Probing the Physics of Baryon Cycles and Feedback using Deep Observations of Nearby Galaxies

Initiative II: Deep Observation of a Galaxy Cluster to Understand Key Physical Processes

Following a call for proposals, two review panels were constructed, one for each initiative, composed of topical experts from the astrophysical community. The proposals were evaluated along several metrics, including their scientific merit, use of *Chandra* capabilities, legacy impact, and alignment with the initiative.

The review committees provided their recommendations to CXC director Pat Slane, and the following programs were selected:

For Initiative I:

A Treasury Survey Probing the Baryon & Energy Cycle and X-ray Binary Evolution in Galaxies at High Angular Resolution *(PI: Smita Mathur) with an award of 2.9 Ms.*

For Initiative II:

The Sounds of Feedback: Deep and Wide Imaging of the Cool Core of the Perseus Cluster *(PI: Andrew Fabian) with an award of 3.0 Ms.*

The programs will run in parallel over the course of Cycles 26 and 27, which nominally begin in January 2025 and January 2026, respectively.

For more information about the selected programs, please visit the CLP website, where you can find the full proposal abstracts.

Celebrating 25 Years of Science with *Chandra*

Amruta Jaodand and Dan Schwartz for the Organizing Committees

Conference Rationale

Launched on July 23, 1999, the *Chandra* X-ray Observatory remains at the forefront of astronomy, mapping the high energy sky at unprecedented angular and spectral resolution. In many ways, the launch of *Chandra* captures the arc of X-ray astronomy—starting with the original 1976 proposal by Riccardo Giacconi and Harvey Tananbaum. It took another 23 years of persistent efforts from astronomers, a leap of technology maturation, and a rescoping of the mission for that vision to be realized as one of NASA's four Great Observatories. Of those four, *Hubble* and *Chandra* remain operational today, with *Chandra* still single fault tolerant and performing observations at near-launch efficiency.

Twenty-five years on, *Chandra* is still a powerful mission, with its sub-arcsecond resolution enabling orders of magnitude improvement in X-ray imaging capability. The combination of high spatial, spectral, and timing resolution, along with deployment in a highly elliptical orbit, allows *Chandra* to conduct deep exposures unencumbered by the charged particle environments that surround Earth. The request for *Chandra* time therefore remains strong, with an oversubscription rate exceeding 4.5 times the available time in recent years.

Chandra has continued to revolutionize our understanding of various domains of astronomy, such as stellar science, accretion and jets, time-varying transients, galaxy formation and AGN feedback, and cluster physics and cosmology. Very recent *Chandra* discoveries include new constraints on the neutron star equation of state through investigations of cold neutron stars in supernova remnants, identification of nearby stars that could host habitable planetary systems, discovery of the exhaust vent in the Galactic Center, and the detection of the most distant supermassive black holes. Many of these science ideas were not even thought of at the time of the launch of *Chandra*.

In fact, the continued impact of *Chandra* discoveries can be witnessed through the more than ten thousand refereed publications based on *Chandra* data, which have been cited almost half a million times. With a continuing publication rate of around 400 publications per year, *Chandra* is one of the most prolific scientific observatories in the world. Impressively, *Chandra* datasets have also contributed to 729 PhDs, which directly reflects the mission's impact in training young astronomers. And, as the mission continues, it leaves a growing legacy: twenty-five years of archival observations and a robust and well-documented source catalog.

Chandra's sharp X-ray vision combined with high-resolution spectroscopy have produced some of the most detailed images, spectra, and light curves of variable and energetic X-ray sources in the universe. These unique capabilities are critical as we step into new eras of time domain astronomy, gravitational wave astronomy, and deep infrared astronomy. From *JWST and Euclid* to the *Roman* Space Telescope and the Rubin Observatory, and in conjunction with LIGO-VIRGO-KAGRA, the next ten years are poised to be full of new sources and new discoveries; *Chandra* is crucial to gain a comprehensive understanding of celestial objects in this panchromatic and multi-messenger future of astronomy! While *JWST*, *Roman*, and Rubin will continue the scientific legacy of some of the great observatories, there is no replacement on the horizon for *Chandra* yet.

This year, with *Chandra* having completed twenty-five years in operation, we celebrate its rich scientific legacy and the discoveries that await us!

A Celebratory Symposium

The *Chandra* X-ray Center is pleased to announce the "25 Years of Science with *Chandra* Symposium," to be held December 3–6, 2024, in Boston, Massachusetts, highlighting and celebrating the rich scientific legacy of *Chandra*.

The symposium will cover various areas in X-ray astrophysics where the spatial, temporal, and spectral resolution of *Chandra* have played a key role, as well as the landscape of *Chandra* discoveries that lie ahead. Eleven invited speakers, covering diverse demographics and career stages, have committed to review and forecast those topics. We anticipate scheduling about 50 contributed talks of 15 minutes each (including questions) and over 100 posters, with extended breaks with refreshments for poster viewing and discussion.

The long-time NASA Project Scientist, Martin Weisskopf, and the founding CXC Director, Harvey Tananbaum, will share their experiences with the development of the mission and its scientific impact, and the STS-93 astronauts will share some of their memories on the opening afternoon.

Full details can be found on the Symposium website: cxc.harvard.edu/cdo/symposium_2024/.

The science achieved by the *Chandra* X-ray observatory is made possible by the tireless efforts of many partners working together as a single *Chandra* team, by strong community interest, and by the participation of thousands of astrophysicists worldwide. We hope the symposium will bring together everyone who has been a part of this wonderful journey to celebrate the twenty-five years of *Chandra*.

Abstract submission is currently open (at this link), with a deadline of August 11; we are accepting abstracts for both talks and poster presentations. Speakers should expect to be notified by September 13.

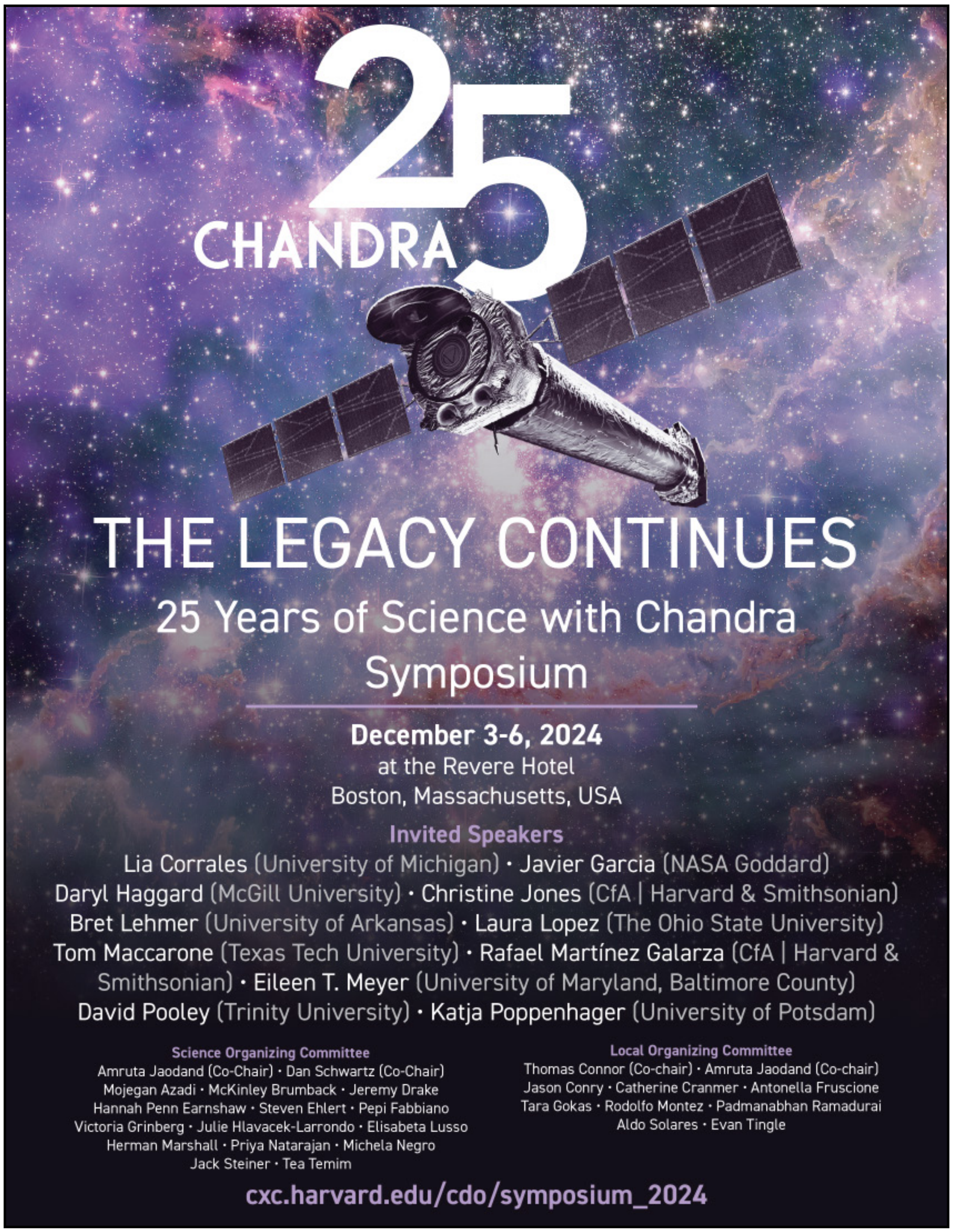
Registration is currently open (on Eventbrite) to everyone, with a regular registration deadline of October 25. Regular registration is $600, or $300 for students. The deadline for both late registration and poster submission is November 8.

The meeting will take place at the Revere Hotel in downtown Boston. The Revere is a block away from Boston Common and easily accessible by public transit. We have reserved a block of rooms, which are available from Monday, December 2, to Saturday, December 7, at only $169/night. Room reservation information can be found on the conference website.

Important dates for the meeting include:

Abstract Submission Deadline:	August 11, 2024
Speakers Notified:	September 13, 2024
Program Release:	September 20, 2024
Regular Registration Deadline:	October 25, 2024
Late Registration and Poster Submission Deadline:	November 8, 2024
Start of Symposium:	December 3, 2024

Don't forget to submit your abstract by August 11!
We look forward to seeing you this December.



Cycle 26 Peer Review Update

Rodolfo Montez Jr.

The Chandra Peer Review has changed significantly over twenty-five years in response to updates in technology and evolving best practices, but it has always maintained at its core a reliance on the efforts of the community and a focus on maximizing the scientific value of the observing plan. What started as a process that relied on mailed-in paper proposals and reports saved on floppy disks now depends on a host of modern software to manage a fully remote dual-anonymous review.

Once again, 99 reviewers volunteered their time and expertise this summer to discuss the 406 proposals submitted to *Chandra*'s 26th call for proposals. Proposals were discussed in eleven topical panels, two Target Of Opportunity (TOO) panels (see last Issue's article for more details), and a Big Project Panel. However, this year all of the events took place from late May through the end of June—instead of the nominal two week period.

Embracing Asynchronous Panels

In 2020, we were forced to switch from our usual in-person review format due to the onset of the COVID-19 pandemic; instead, we embraced online tools—Zoom, Slack, and Google Drive—to enable a fully-remote review. For a variety of reasons, especially the costs, *Chandra* Peer Review has remained fully-remote, even after other in-person events have resumed. There have certainly been drawbacks to not meeting face-to-face, but the format does allow for more flexibility for participants, who can now participate in the review without the complexity of multi-day travel.

This year, we extended that flexibility even further. One of the major impediments to the recruitment of scientists serving on panels is that June, when we traditionally hold our peer review, is also an active season for conferences and vacations. A single high-impact topical meeting could potentially deprive the review of dozens of qualified reviewers. If the topic of the conference were to overlap with a focus of one of our panels, it could dramatically hamper recruitment. Prior to 2020, we were required to have all panels meet at the same time in order to work within the confines of having the Review at a single venue. With online panels, that restriction is no longer present, and so this year we conducted our first review with asynchronous panels.

Panels 3 and 4 met the week of May 27, Panels 1 and 2 the week of June 3, and Panels 5–13 the week of June 17, followed by the Big Project Panel. In addition to allowing flexible scheduling to accommodate panelists' schedules, this format also meant that CXC scientists and staff were better able to provide support as needed. And, with only a maximum of nine panels running concurrently at any time, we were able to optimize staffing and support of all the panels. These factors may seem minor, but with the relatively small CXC support staff, they improved the efficiency of panel operations while also reducing the overall demands on staffing.

This experiment went well, and, with many of the first-run issues worked out, we are currently planning on continuing and improving asynchronous panels in the future.

Cycle 26 Proposal Statistics

Full proposal statistics from Cycle 26 will be released along with the results of the Peer Review on the CXC website. Results will be released at a later date, when there is further clarity about the financial and operational situation of the mission.

A Project Science Retrospective On 25 Years Of *Chandra*

Douglas Swartz (USRA/MSFC), Steven Ehlert, and Steve O'Dell (NASA/MSFC)

Introduction

The Project Science team is pleased to provide this brief retrospective of its role in the formulation, development, calibration, and operation of the *Chandra* X-ray Observatory. Our hope is to help provide today's science community with a well-grounded perspective on the past and to help place our shared current challenges into a broader context, as we mark twenty-five years of *Chandra* scientific achievements.

The Project Science team has always served as the interface between the science community and the project to help ensure the scientific integrity of the mission. We believe *Chandra*'s outstanding record of scientific and technical success is because all components of the project—scientists, engineers, and management and both industry and science institutions—worked together towards the common objective of building and operating the world's greatest X-ray astrophysics facility.

Formulation And Development

The Project Science story began decades before the launch of *Chandra*, when NASA assigned project management responsibility to the Marshall Space Flight Center (MSFC) for a bold X-ray mission initiative proposed in 1976 by a team from the Smithsonian Astrophysical Observatory (SAO), led by Riccardo Giacconi and Harvey Tananbaum. The first Advanced X-ray Astrophysics Facility (AXAF) Project Scientist, Martin C. Weisskopf, was selected and arrived at MSFC by 1977 and began building the Project Science team by 1980. From the beginning, MSFC was responsible for managing AXAF and for preliminary scientific systems engineering studies while SAO provided additional scientific and technical support. By 1985, Project Science became a well-defined collaboration among the Project Science team at MSFC (led by Martin), the SAO Mission Support Team (led by Harvey), and the Telescope Scientist (the late Leon Van Speybroeck, also at SAO).

The first major milestone occurred when the Decadal Survey report for the 1980s recommended AXAF as the top priority major national space observatory, specifically recognizing the importance to the entire astronomy community of a Flagship X-ray observatory. High-resolution X-ray mirrors were soon identified as the highest technological challenge to the project. This led to the Project Science team overseeing the immediate development of the Technology Mirror Assembly (TMA)—a 2/3-scale version of the AXAF innermost mirror pair, having a 6-meter focal length—and testing it in the existing X-ray Calibration Facility (XRCF) at MSFC. Testing was performed in 1985 and again after additional figuring and polishing of the optic in 1989. The success of these tests gave the project confidence that the biggest technological hurdles could be overcome.

Despite these and other successes, Congress mandated that continued mission development funding required demonstration of sub-arcsecond X-ray imaging capability with the largest AXAF mirror pair before the end of fiscal year 1991. Confirmation of the requisite performance was made by testing the so-called Verification Engineering Test Article (VETA) in the refurbished XRCF, thereby avoiding outright cancellation of AXAF. At about the same time, the 1991 Decadal Survey re-affirmed AXAF as the highest priority large program for astronomy and astrophysics. In addition, SAO was competitively selected to operate the AXAF Science Center, what would later be called the *Chandra* X-ray Center.

Still, major challenges abounded. Critically, NASA directed an extensive restructuring in 1991 and 1992 to reduce costs and to help secure continued congressional support. This was a major undertaking for Project Science and for the entire project, involving numerous trade studies to maximize scientific return within project resource constraints. The result was a split of the mission into two satellites: one, called *AXAF-I*, would have an emphasis on high-resolution imaging, but with only 4 of the original 6 mirror pairs; the other, called *AXAF-S*, would carry the microcalorimeter high-resolution spectrometer as its only science instrument. In 1993, Congress canceled *AXAF-S*, relegating the microcalorimeter to eventually fly on JAXA's *Suzaku* mission over a decade later. *AXAF-I*, what is today the *Chandra* X-ray Observatory, did survive with a new, lighter weight, its present complement of instruments, a non-serviceable, highly elliptical-orbit, and the remaining 4 HRMA mirror pairs now with Ir coatings.

Fortunately, funding stabilized after 1994 and remained relatively steady throughout the rest of development, calibration, and deep into science operations by successfully overcoming numerous key decision points, independent and semi-independent reviews and assessments (including all 7 Senior Reviews of Operating Missions), and many other programmatic and technical hurdles.

The primary Project Science role during the formulation and development stages was overseeing development and testing of TMA and VETA at XRCF and performing modeling and analyses to support mission trade studies during restructuring. These studies included effective area trades for different mirror configurations and mirror coatings and the formulation of science requirements and optics designs for the *AXAF-S* mission. After restructuring, Project Science team efforts at MSFC concentrated on detailing science requirements that flow down to technical specifications, establishing HRMA particulate and molecular contamination requirements, identifying and suppressing potential sources of background noise (such as baffling UV-to-IR stray light), and shielding against charged particle and X-radiation, among many other studies.

Calibration

MSFC Project Science had primary scientific responsibility for the *Chandra* ground calibration effort at the XRCF. This was a large undertaking culminating in a 6-month-long, 24/7 exercise beginning late in 1996. The calibration test sequence included calibration of the HRMA flight optics (alone and in conjunction with the LETG and HETG assemblies) and of the HRC, the ACIS-2C (a custom-built two-CCD surrogate ACIS with one BI and one FI chip), and finally ACIS itself, first with the mirrors and gratings and then alone after the HRMA was sent to final assembly and integration. Flight instrument calibration was preceded with calibration rehearsals in the summer of 1996 using the Au-coated TMA coupled with TOGA—the TMA Objective Grating Assembly, a custom grating assembly populated with flight-type LEG, MEG, and HEG grating facets—and a large suite of ground support hardware.

Project Science, with inputs from SAO and the instrument teams, wrote the calibration requirements document that specified the types of tests and the X-ray support equipment required for test implementation. Project Science also co-led the team that planned and executed the calibration and coordinated efforts to resolve issues in calibration data analysis, while the AXAF Science Center had primary responsibility for data ingestion, analysis, and documentation in collaboration with the science instrument teams and the Telescope Scientist.

Operations

Since the launch of *Chandra* and the start of science operations in 1999, Project Science has primarily held an advisory role supporting the MSFC Program Manager and the CXC leadership. Project Science has actively participated in resolving several anomalies in the scientific performance of the instruments, the following two being among the most notable:

(1) *The rapid degradation in CCD performance during initial operations*, with the Project Science team helping identify the cause as radiation damage by low-energy protons scattered off the X-ray mirrors onto the focal plane; supporting formulation of a subsequent radiation management program; and developing with the MSFC space environments group the *Chandra* Radiation Model, which is used to estimate proton fluence throughout *Chandra*'s orbit.

(2) *The loss in ACIS low-energy efficiency*, with the Project Science team helping establish the cause as accumulation of molecular contamination onto the Optical Blocking Filters; supporting an extensive CXC-led investigation of the anomaly and how to mitigate it, including simulating a bakeout of the instrument; and supporting calibration efforts to quantify and to model the ongoing time-dependent change in efficiency.

Importantly, Project Science has worked to maintain a strong knowledge base by conducting scientific research—especially with *Chandra*—throughout the science operations phase. This research work helps us to gain a user's perspective that enables Project Science to better identify issues impacting General Observers and to ensure fair and equitable use of *Chandra* by its increasingly diverse and evolving science community.

The first peer-reviewed scientific contribution from Project Science was, not surprisingly, an analysis of Crab Nebula spatial and spectral structure, led by the long-time Project Scientist Martin Weisskopf. Now, just within the past several months, Project Science team members at MSFC have authored or co-authored (1) an investigation of the effect of AGN heating on the disruption of cooling cores in a large sample of clusters, (2) the discovery with *Chandra* of Fe emission line complexes, extending to several arcsecond scales in a nearby Compton-thick AGN (where 1″~ 200 pc), and (3) research showing a newly-detected XRB can power an outflow in a nearby luminous compact galaxy, enabling Lyman-continuum emission to escape the galaxy.

Summary

Project Science has served as an interface between the science community and the *Chandra* project for nearly five decades. Assisting individuals and organizations involved in the project helps to serve the needs of the thousands of scientists who utilize *Chandra* for astrophysical research and contribute to *Chandra*'s outstanding record of success. As we celebrate twenty-five years of *Chandra* operations, Project Science stands committed to helping preserve *Chandra* for the future benefit of the world's astrophysics community.

Orion Nebula

Credit: X-ray: NASA/CXC/SAO; Infrared: NASA/ESA/CSA/STScI/M. Mccaughrean, S. Pearson; Image Processing: NASA/CXC/SAO/K. Arcand and J. Major

HETG: 25 Years of Dispersion

H. M. Günther, Sean Gunderson, and Ioanna Psaradaki for the HETG team

Current status

The HETG continues to perform nominally with no signs of aging, and demand from proposers remains strong. For Cycle 25, 76 HETG observations of 18 unique targets are planned for a total of 1.8 Ms; 60 of those observations have been performed successfully as of May 2024. Furthermore, the first TOO observation of cycle 25—a bright stellar mass black hole in a windy state (Swift J1727.8-1613, PI: Miller)—was performed in October 2023.

HETG use over time

Up to now, the HETG has observed about 400 unique objects, many of them more than once. The exact number is a bit hard to count, as some HETG pointings are set with the aimpoint deliberately placed in empty space to get spectra from two (or more) sources in the field of view. In other cases, the HETG might look at separate targets in separate pointings so close to each other that they somewhat—but not entirely—overlap. Six objects have accumulated more than 1 Ms of HETG data, ranging from stars to galaxies: η Car, HD 37022 (also known as θ^1 Ori C, the center of the Orion nebula cluster), NGC 3783, NHC 4041, Sgr A*, and SN 1987a. Sgr A*, in particular, has reached almost 3 Ms of exposure time. Over the life of the mission, the average length of an individual HETG observation has been decreasing as many HETG observations are broken up into different ObsIDs for scheduling reasons. However, for many sources it is their time variability that really makes them interesting, and repeat observations allow us to look into changes over time for a wide variety of sources with more than one ObsID.

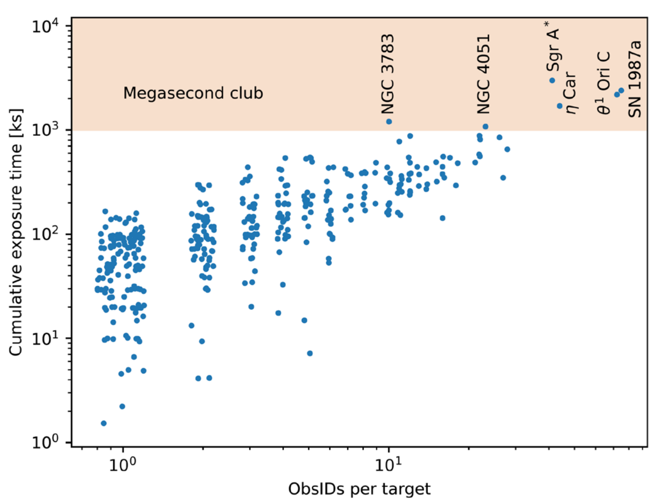


Figure 1: Unique targets observed with Chandra/HETG, with small extra scatter on the x-axis to avoid overlapping symbols. Many targets are observed more than once. In the html version of this newsletter, the figure is interactive, and you can hover over individual objects to learn more about them.

You can teach an old dog new tricks

Over time, the HETG instrument team and *Chandra* observers have found new ways to learn more from HETG observations and use the instrument in creative ways to overcome limits on brightness, ACIS contamination, source confusion, and resolving power.

HETG/HRC

In the 2010's, the contamination on ACIS increased so much that the HETG signal at wavelengths longer than 15 Å essentially disappeared; today even the Ne IX triplet (~12 Å, 1 keV) is difficult to observe. The HETG team thus experimented with using the HRC as a detector. As an added twist, we tested with HRC-I, not HRC-S, because of its lower background (for further details, see the HETG update in Issue 25). Unfortunately, the current temperature constraints that limit the use of the HRC mean that this option has not been used much in practice.

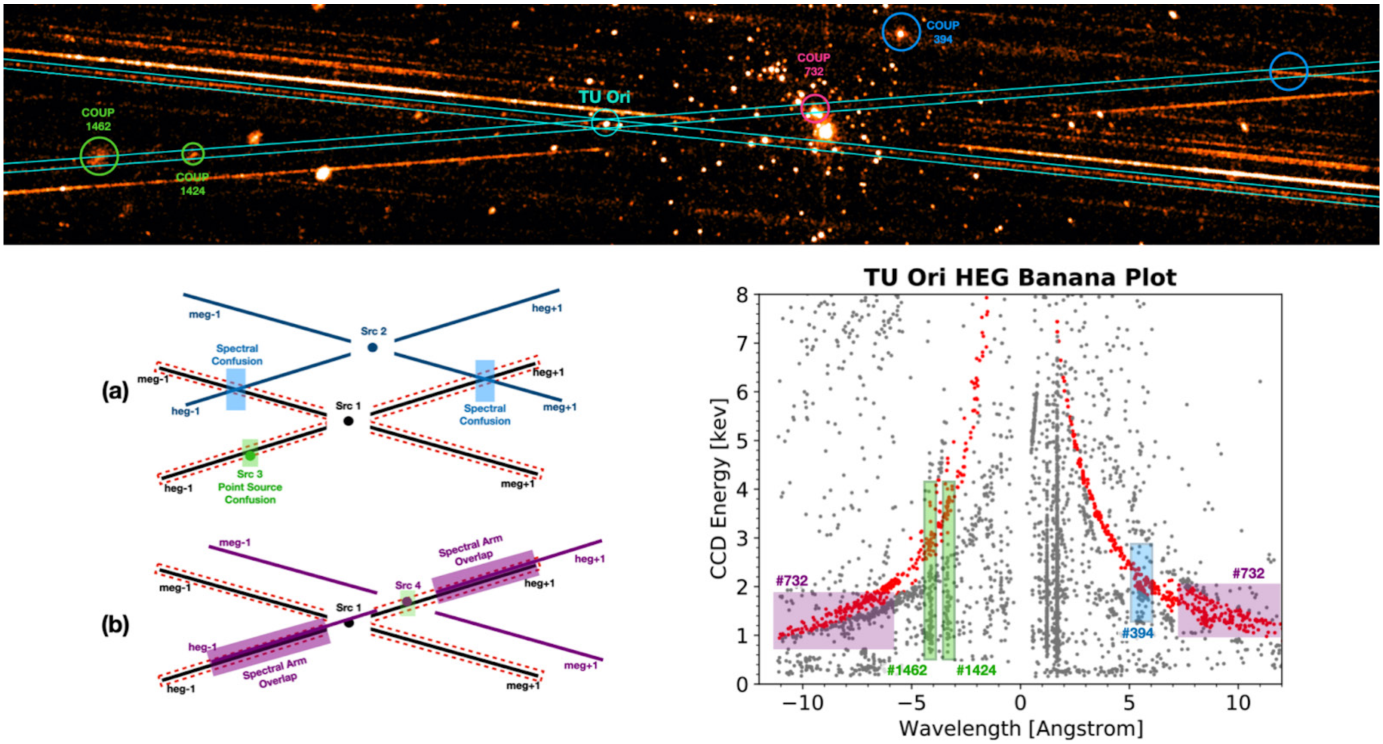


Figure 2: ***Top***: *An HETG observation of the star-forming Orion Nebula Cluster, a region with more than 1,600 pre-main sequence X-ray emitting stars. The dispersed spectrum of TU Ori is displayed (cyan rectangles) with sources of confusion highlighted with circles (green: point sources overlapping the HEG−1 arm; blue: an MEG arm from COUP 394 overlaps the HEG arm from TU Ori; magenta: COUP 732 is dispersed in the same direction as TU Ori and the entire spectral arm overlaps).* ***Left***: *An illustration (not to scale) demonstrating (a) a point source (green) and a spectral arm (blue) confusing a small part of the target spectrum and (b) a situation where entire spectral arms overlap (magenta). The black X labeled Src 1 shows the arm locations for HEG and MEG for the target source, while the red dashed box encloses the extraction region.* ***Right***: *ACIS order sorting banana plot showing confused events from different sources in the field erroneously being assigned to the spectra of TU Ori. Red dots indicate events that standard CIAO processing assigns to the extracted source (TU Ori) while other events, whose CCD-resolved energy do not match the expected wavelength of TU Ori, are not included in the standard CIAO source extraction. Colored numbers represent the COUP number of the source causing confusion for this case. Examples where standard CIAO processing has the potential to erroneously include events from other sources in the extracted spectrum of TU Ori are shown as red dots within the colored boxes. This figure is from Schulz et al. (2024).*

Crowded fields

Since the HETG is slitless, every source in the ACIS-S field with sufficient flux will cast its own HETG-characteristic X-shaped pattern on the CCDs. This makes reducing observations of complicated fields like supernova remnants or crowded regions like young stellar clusters challenging. In such fields, one must account for scenarios such as two sources' dispersed spectra overlapping or a 0th order point source landing on a dispersed spectrum of interest (both of these scenarios can be seen in Figure 2). In some cases, the CCD energy resolution helps with order sorting; we know from the grating equation which wavelengths are expected at which detector positions. If we are lucky, the wavelengths of two crossing arms are sufficiently far apart that the ACIS CCD energy resolution can separate them. If not, we cannot discern which source contributes how many photons in the overlap region,

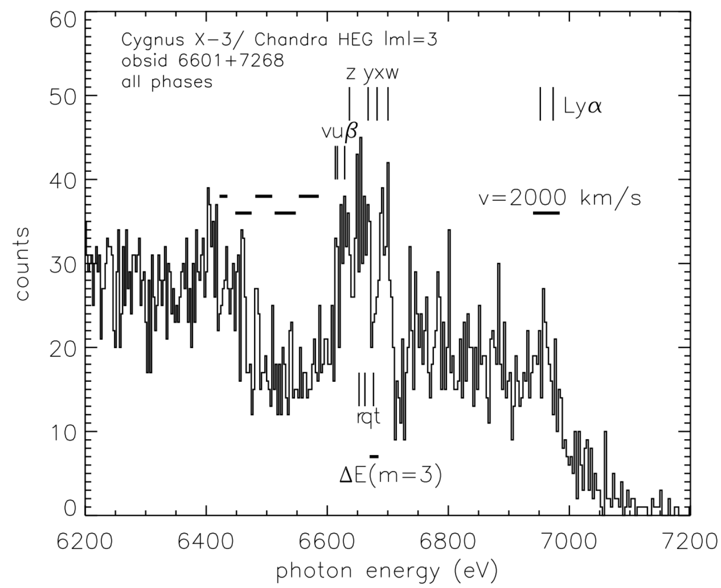


Figure 3: *Third-order HETG spectrum from Cygnus X-3. The approximate resolution of 15 eV at 6.7 keV is indicated, as are the position of several spectral features. This figure is from Suryanarayanan et al. (2022).*

and we need to exclude this part of the spectrum from spectral fitting. HETG team member D. Principe has developed software to work out geometric relations to identify and mask spectral overlap, which has been instrumental in observations of the Orion Nebula Cluster (ONC) to extract HETG spectra from the more than 40 sources in each of the ONC observations (Schulz et al. 2024).

Sometimes less is more

For bright sources, Continuous Clocking (CC) Mode can reduce the impacts of pileup, but it comes at the cost of requiring extra care in separating MEG and HEG spectra. Yet even in CC Mode, stellar mass black holes in outburst can be so bright that they saturate the telemetry. V404 Cygni in outburst is one such source (King et al. 2005); to mitigate both problems, the source was placed just at the edge of ACIS-S so that only two arms (one MEG and one HEG arm) fall on the ACIS-S chips. Nevertheless, telemetry saturation still led to chips dropping out during the observation. The same strategy has been employed for more recent observations of very bright sources.

Higher diffraction orders

When sources are bright, observers can also look at higher diffraction orders. Because those higher orders are located further away from the zeroth order, they offer a better spectral resolving power. Suryanarayanan et al. (2022) analyzed the Fe K spectrum of Cygnus X-3, a high mass binary; they aimed to separate a plethora of separate Fe lines, which they interpret as resonantly scattered emission from inner shells. While the interpretation is complicated—as is appropriate for such a complicated binary system—it does show the value of pushing to better spectral resolution, which we can do by using the higher orders of the HETG.

What have we learned in 25 years of grating observations?

Chandra/HETG data has been used in about 1200 refereed papers so far, and it is impossible to review the breadth and depth of all fields studied in a single newsletter article. Nevertheless, in addition to star-forming regions and galactic binaries discussed above,

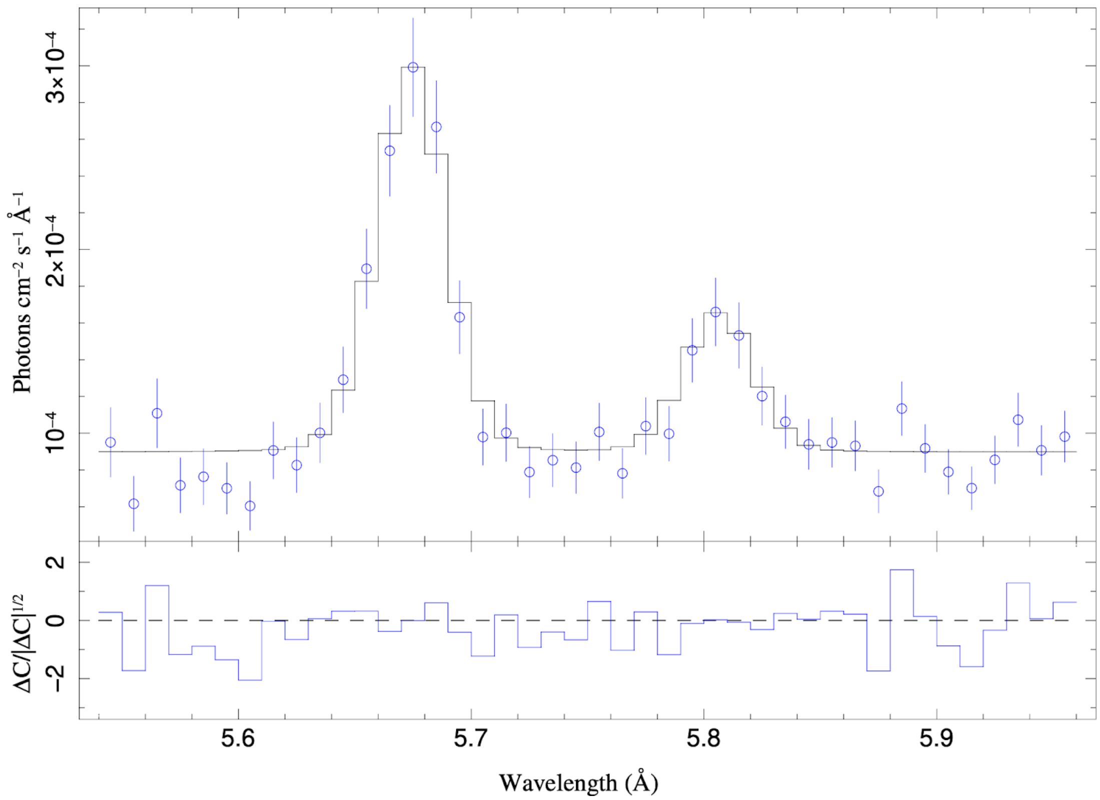


***Figure 4:** Si XIII He Lyman β and associated DR satellite line in the HEG+MEG spectrum of ζ Puppis. A two Gaussian model fit is applied to the data, which consist of 813 ks of observations from Cycle 19. This figure, which is from Gunderson et al. (2023), shows HEG+MEG data plotted on the MEG grid.*

we want to highlight just a few examples that have seen consistent interest in the last 25 years and show how far we have come.

Capella and stellar coronae

The chromospherically active binary star Capella has been observed regularly since the launch of *Chandra* because it is used as a calibration source for the HETG and LETG. It can also serve here as a prime example of how much we've learned about stellar coronae in the past two and a half decades of grating observations. In the early days, observers were overwhelmed with the wealth of emission lines suddenly available to them and quickly started to use them to benchmark and improve the atomic data for the complex Fe lines in the Capella spectrum (Behar et al. 2001). Before *Chandra*, coronae were described with two or three plasma temperature components at best, but with the HETG—as well as *Chandra*/LETG and *XMM*/RGS—it was suddenly possible to determine detailed distributions of temperatures from the large number of separate emission lines (Gu et al. 2006).

As the archive grew over time, studies of temporal variability became possible. With the exceptional calibrations and spectral resolving power, such studies for Capella also included measuring the change in line position over time. Combining measured line shifts with known orbits of the Capella components shows that the X-ray emission is dominated by the G8 III giant while the hotter G1 III seems to be much fainter in X-rays (Ishibashi et al. 2006). Studies of line kinematics (e.g., Bozzo et al. 2023) as well as the work on Fe emission line benchmarking (see Gu et al. 2022 for a recent example) continue to this day.

Massive stars

Over the last 25 years, *Chandra*'s HETG has deepened our understanding of the winds of O, B, and Wolf–Rayet stars. The first observations of O stars confirmed that X-rays are produced by shocks distributed through the wind (Waldron & Cassinelli 2001; Cassinelli et al. 2001). Later observations were then used to calculate clumping-independent mass-loss rates, which were found to be up to an order of magnitude less than those calculated from theory and using longer wavelengths (Cohen et al. 2014). The wealth of observations made with the HETG on these hot stars has also brought into context the similarities in the shock generation between these stars (Cohen et al. 2014; Gayley 2016)

More recently, dielectronic satellite lines were found for the first time in a hot star's X-ray spectra (Gunderson et al. 2023), although almost 1 Ms of observation time on ζ Puppis was needed to see them. These lines can be used to probe the plasma conditions of the shocks while staying independent of elemental abundances. Gunderson et al. (2023) used the dependence of these lines on the temperature distribution to test the assumption that hot star wind shocks reach collisional ionization equilibrium. Their test confirmed collisional ionization equilibrium as the valid plasma state, opening new spectral analysis avenues in other hot stars.

Dust in the universe

Over the last 25 years, using measurements of absorption of X-rays from bright sources the high-resolution X-ray spectrometers aboard *Chandra* have yielded remarkable findings in the study of the interstellar medium and dust mineralogy. During the early years of *Chandra*'s operation, numerous studies explored X-ray photoabsorption edges and features arising from the ISM in the Milky Way. Schulz et al. (2002) examined the first high-resolution X-ray spectrum of Cygnus X-2 with HETGS, focusing on the structure of the O K, Ne K, Mg K, and Si K edges. Later, Juett et al. (2004) conducted a detailed examination of the oxygen K-shell interstellar absorption edge in seven X-ray binaries, identifying various absorption lines from neutral, singly ionized, and doubly ionized oxygen. Lee et al. (2002) reported the detection of the first astrophysical signature of X-ray absorption fine structure in the photoelectric edge of Si, which was attributed to material in dust grains. Finally, Ueda et al. (2005) studied the ISM towards

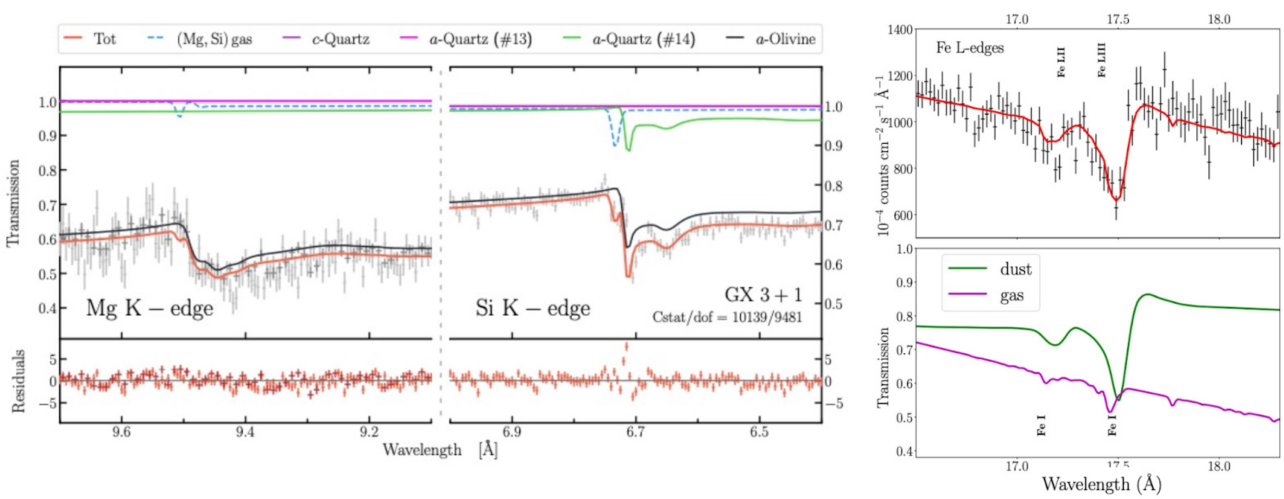


Figure 5: *Left: Chandra/HETGS data and best fit in the Mg K and Si K-edges from Rogantini et al. (2020). Right: Best fit in the O K and Fe L-edges for SWIFT J1910.2–0546 and the relative transmission for the gas and dust components (Psaradaki et al. 2023).*

***Figure 5**: Reactive Ion etch plasma tool at MIT's Space nanotechnology laboratory (ca. 1995).*

three Galactic X-ray binaries—GX 13+1, GX 5-1, and GX 340+0—detecting X-ray Absorption Fine Structures (XAFS) of dust around the Si K-edge. These studies paved the way for studies on dust grain chemistry using the X-ray band.

In more recent years with *Chandra* a plethora of studies have focused on X-ray binaries, with an emphasis on exploring the chemical enrichment of our Galaxy. Costantini et al. (2012) investigated the joint *Chandra* and *XMM-Newton* high-resolution X-ray spectrum of 4U 1820-30 in the O K and Fe L edges, utilizing dust grain models to find slight over- and under-abundances of oxygen and iron, respectively. Additionally, studies by Zeegers et al (2019), Rogantini et al. (2019), and Psaradaki et al. (2023) analyzed the Si K, Mg K, and Fe L edges in HETGS spectra of various X-ray sources along the Galactic plane, employing an up-to-date dust extinction model computed from laboratory data. These authors revealed insights into the chemistry, crystallinity, and size distribution of dust grains in both dense and diffuse regions of the ISM, highlighting the efficacy of high-resolution X-ray spectroscopy in studying interstellar dust mineralogy.

Look into the future

The HETG has performed exceptionally well over the last 25 years with only one small hiccup: a few years ago there was a small scare about the grating insertion mechanism, which, by folding the HETG in and out behind the mirrors, enables *Chandra* observers to observe with or without the HETG. For a few weeks it seemed that the gratings assembly was not moving enough, but engineers quickly traced that back to be a minor problem with a sensor that measures rotation—the rotation itself is fine. Otherwise, the gratings are stable in space and the facets and holders are not bothered by radiation or increasing temperatures on *Chandra*. There is nothing that prevents the HETG from operating exceptionally well for the next 25 years, so long as the rest of the satellite stays up and running. In particular, the HETG can deal just fine with increased focal plane temperatures; since the wavelength solution comes from the grating equation and not the CCD resolution, HETG observations can be done at higher focal plane temperatures than imaging observations. This provides better flexibility and observing efficiency for scheduling observations.

All that glitters

Yet, as they say, "*Nach dem Spiel ist vor dem Spiel*" (after the game is before the game).

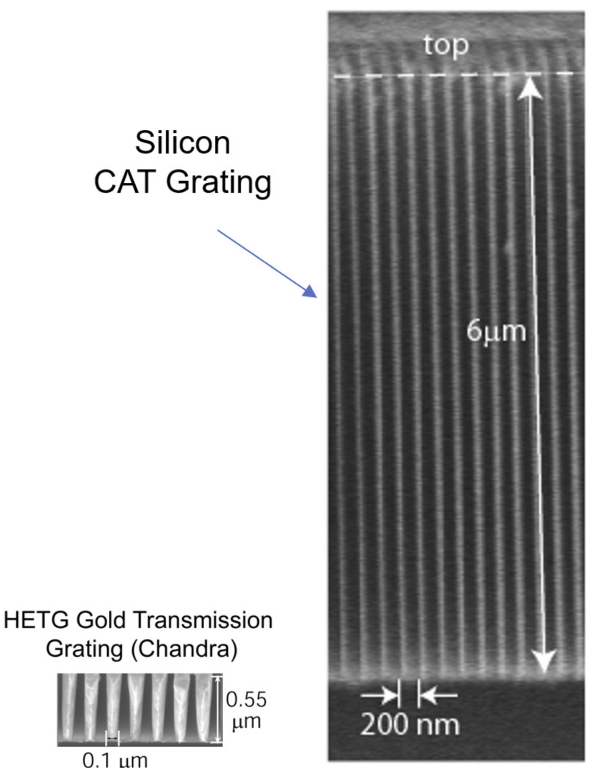


Figure 6: Scanning electron microscope images of cleaved cross sections of a Chandra/ *HETG grating on the left and a modern CAT grating on the right (MIT Space Nanotechnology Laboratory). Note the high aspect ratio and smooth surfaces of the CAT gratings, made possible through continuous improvement of the processes that were used to make the HETG gratings.*

While the HETG is quietly and efficiently working in orbit, the team that invented and built the grating facets for the HETG has been hard at work back on Earth to improve their technology and invent the next big thing: critical angle transmission (CAT) gratings. Those grating bars are etched from silicon wafers (the HETG uses gold) at very high aspect ratios. CAT gratings are mounted such that X-rays hit the grating bar sidewalls at a small incidence angle and "bounce off" to one side. That geometry diffracts most rays into high orders on one side. CAT gratings can reach a resolving power > 10,000 and efficiencies > 20% in the soft X-rays (Heilmann et al. 2022).

These gratings will be used in the upcoming *RedSOX* rocket mission (an under construction X-ray polarimetry mission with 5 minutes of flight time) and are planned for the proposed *Arcus* probe mission and *Lynx* flagship mission to power a worthy successor of the HETG. However, even in the best of cases, these won't launch any time soon—so long live the HETG!

References

Behar, E., Sako, M., & Kahn, S. M. 2001, ApJ, 563, 497.
Bozzo, E., Huenemoerder, D. P., Produit, N., et al. 2023, MNRAS, 522, L66.
Cassinelli, J. P., Miller, N. A., Waldron, W. L., MacFarlane, J. J., & Cohen, D. H. 2001, ApJL, 554, L55.
Cohen, D. H., Li, Z., Gayley, K. G., et al. 2014, MNRAS, 444, 3729.
Costantini, E., Pinto, C., Kaastra, J. S., et al. 2012, A&A, 539, A32.
Gayley, K. G. 2016, AdSpR, 58, 719.
Gu, L., Shah, C., Mao, J., et al. 2022, A&A, 664, A62.
Gu, M. F., Gupta, R., Peterson, J. R., Sako, M., & Kahn, S. M. 2006, ApJ, 649, 979.
Gunderson, S. J., Gayley, K. G., & Huenemoerder, D. P. 2023, MNRAS, 522, 2739.
Günther, H. M. 2018, ChNew, 25, 14.

Heilmann, R. K., Bruccoleri, A. R., Burwitz, V., et al. 2022, ApJ, 934, 171.
Ishibashi, K., Dewey, D., Huenemoerder, D. P., & Testa, P. 2006, ApJL, 644, L117.
Juett, A. M., Schulz, N. S., & Chakrabarty, D. 2004, ApJ, 612, 308.
King, A. L., Miller, J. M., Raymond, J., Reynolds, M. T., & Morningstar, W. 2015, ApJL, 813, L37.
Lee, J. C., Reynolds, C. S., Remillard, R., et al. 2002, ApJ, 567, 1102.
Psaradaki, I., Costantini, E., Rogantini, D., et al. 2023, A&A, 670, A30.
Rogantini, D., Costantini, E., Zeegers, S. T., et al. 2020, A&A, 641, A149.
Schulz, N. S., Cui, W., Canizares, C. R., et al. 2002, ApJ, 565, 1141.
Schulz, N. S., Huenemoerder, D. P., Principe, D. A., et al. 2024, arXiv, arXiv:2404.19676.
Suryanarayanan, A., Paerels, F., & Leutenegger, M. 2022, arXiv, arXiv:2212.04165.
Ueda, Y., Mitsuda, K., Murakami, H., & Matsushita, K. 2005, ApJ, 620, 274.
Waldron, W. L., & Cassinelli, J. P. 2001, ApJL, 548, L45.
Zeegers, S. T., Costantini, E., Rogantini, D., et al. 2019, A&A, 627, A16.

Updates from the Low Energy Transmission Grating

Brad Wargelin for the LETG Team

Back on Schedule

With the HRC'S Return to Science in April 2023 (see Issue 33) now well behind us, the associated backlog in LETG observations has been fully cleared. The last observations from Cycles 22, 23, and 24 were all completed by Oct 2023, and as of June 2024 there is only one more non-Calibration target from Cycle 25 remaining (for 59 ks), scheduled for fall 2024. Another milestone is the recently completed (mid-June) increase in the HRC high voltage to restore detector gain and QE to their pre-pandemic levels. As with previous HV increases in 2012 (HRC-S only) and 2021, it will take a few months for results of the new QE calibration to be included in the CALDB, but observation scheduling should not be significantly affected.

By the Numbers

	Sources	Total Exposure (ks)	TOO & DDT Exposure (ks)
Active Galaxies & Quasars	34	6658	984
Stars & White Dwarfs	52	6037	19
Supernovae, Supernova Remnants, & Isolated Neutron Stars	17	4251	958
White Dwarf Binaries & Cataclysmic Variables	41	2560	1371
Extragalactic: Diffuse & Surveys	8	2110	746
Black Hole & Neutron Star Binaries	20	1323	370
Galactic: Diffuse & Surveys	8	610	94
Solar System & Exoplanets	6	228	113

The current lull in LETG observations, along with *Chandra*'s 25th anniversary, inspires a look back at how observers have been using the LETG. To date, the total non-Calibration LETG exposure time is 25038 ks (1.13 years assuming 70% *Chandra* observing efficiency), accumulated over 593 ObsIDs. The distribution among source categories is listed in Table 1.

TOOs account for 3398 ks of LETG exposure, while DDT observations contribute an additional 1256 ks. The source with the most LETG DDT exposure is RX J1856.5−3754, a nearby isolated neutron star, which was observed for 441 ks in Oct 2001. Including GTO and calibration observations, RX J1856.5−3754 has a total LETG exposure of 1206 ks. Other sources with substantial LETG Calibration time include Capella (808 ks, all from Calibration) and Mkn 421 (4833 ks total, of which 4463 ks was for Calibration). The former source is used for calibration of the line response function and dispersion relation monitoring, as well as effective area cross-calibration between HETG and LETG for HRC-S and ACIS-S, while the latter source is observed primarily to monitor contaminant buildup on ACIS; Mkn 421 therefore has the greatest exposure time of any target observed by the LETG. As well as being calibration targets, Capella and Mkn 421 are also notable as exemplars of the two broad classes of LETG science: studying line emission and absorption.

Coronae and Capella

Capella is a stellar binary consisting of G8 and G1 giants, with most of the X-ray emission coming from the G8; at a distance of 13.12 pc, Capella is the brightest coronal source in the sky—other than the Sun, that is. The first LETG/HRC-S observations of Capella were focusing observations taken in early Sep 1999, with longer observations following on Nov 9 (85 ks using LETG/HRC-S) and Nov 10 (54 ks using LETG/ACIS-S). Its *Chandra* spectra were first presented in Brinkman et al. (2000) and cited in Issue 8 but, apart from a few narrow glimpses, the Capella spectrum has amazingly never appeared in this august publication. LETG observers have probably seen those data many times, however, in Figure 9.26 of the Proposers' Observatory Guide. And for those who prefer a Ken Burns-style presentation, Vinay Kashyap and Thomas Connor have created a movie of the Capella spectrum from HETG and LETG data at https://youtu.be/a6rCzrGOQys. With resolving power of up to R~2000 and wavelength coverage out to ~175 Angstroms, Capella spectra have been invaluable for improving the atomic data used in spectral modeling (including energy levels, electron collision excitation cross sections, and dielectronic recombination resonance strengths), allowing much more accurate use of temperature and density line ratio diagnostics in high-resolution spectra and higher-quality fits to lower-resolution CCD spectra.

Backlit Baryons and Mkn 421

Mkn 421, a BL Lac object (roughly synonymous with "blazar," an AGN with its relativistic jet aimed at us) illustrates the other prime use of the LETG: studying interstellar or intergalactic gaseous material such as the Warm Hot Intergalactic Medium (WHIM) or Galactic dust grains through their absorption of a bright continuum source. Due to its abundant data, Mkn 421 has been a valuable target for both sets of searches, directly (Nicastro et al. 2005) and indirectly (Staunton & Paerels 2023).

In the broader sample of LETG observations, Galactic absorption features have been confidently measured (e.g., Paerels et al. 2001; Wang et al. 2005; Williams et al. 2007), but WHIM detections remain tantalizingly tentative with mostly marginal S/N (Fang et al. 2002; Nicastro et al. 2005; Zappacosta et al. 2010; Kovács et al. 2019). Likewise, there are *Chandra* grating detections of dust absorption (Valencic & Smith 2013; Rogatini et al. 2020;

Staunton & Paerels 2023), but uncertainties in laboratory spectral data—particularly energy—prevent secure conclusions regarding dust grain compositions. More compelling WHIM detections will probably have to await a future X-ray observatory with significantly larger effective area (a disappointingly distant prospect), while progress on studies of dust composition will also require better energy calibration of lab measurements.

Notable Novae

In addition to over 4 Ms of calibration observations, Mkn 421 has a substantial 393 ks of TOO/DDT exposure in observations intending to catch the source when it is particularly bright. Yet even with that boost, the "Active Galaxies and Quasars" category is not the most popular category for LETG TOO/DDT observations, by either total time or fraction of time. The winning category is "White Dwarf Binaries and Cataclysmic Variables," which, with over 50% of its total 2560 ks of LETG exposure devoted to TOOs and DDTs (mostly of novae), could also be well described as "Things That Go Boom." Spectra of novae tend to be a messy mix of temporally evolving components and are therefore extremely challenging to model in detail. Soft X-rays become visible a week to several weeks after the optical eruption; known as the supersoft source phase (SSS), the ejecta has thinned enough at this point that a blackbody-like spectrum from the bloated photosphere of the white dwarf is seen. Steady nuclear burning continues on the white dwarf surface during the SSS phase, and the spectrum shows mostly blueshifted absorption lines from the radiatively-driven outflow. Sometimes emission lines are also observed, likely resulting from an edge-on view of the outflow in the presence of the accretion disk or, at later times, from shocked and photoionized ejecta. A recent paper by Milla & Paerels (2023) analyzes LETG spectra from Nova Delphini 2013 (see Figure 1) and com-

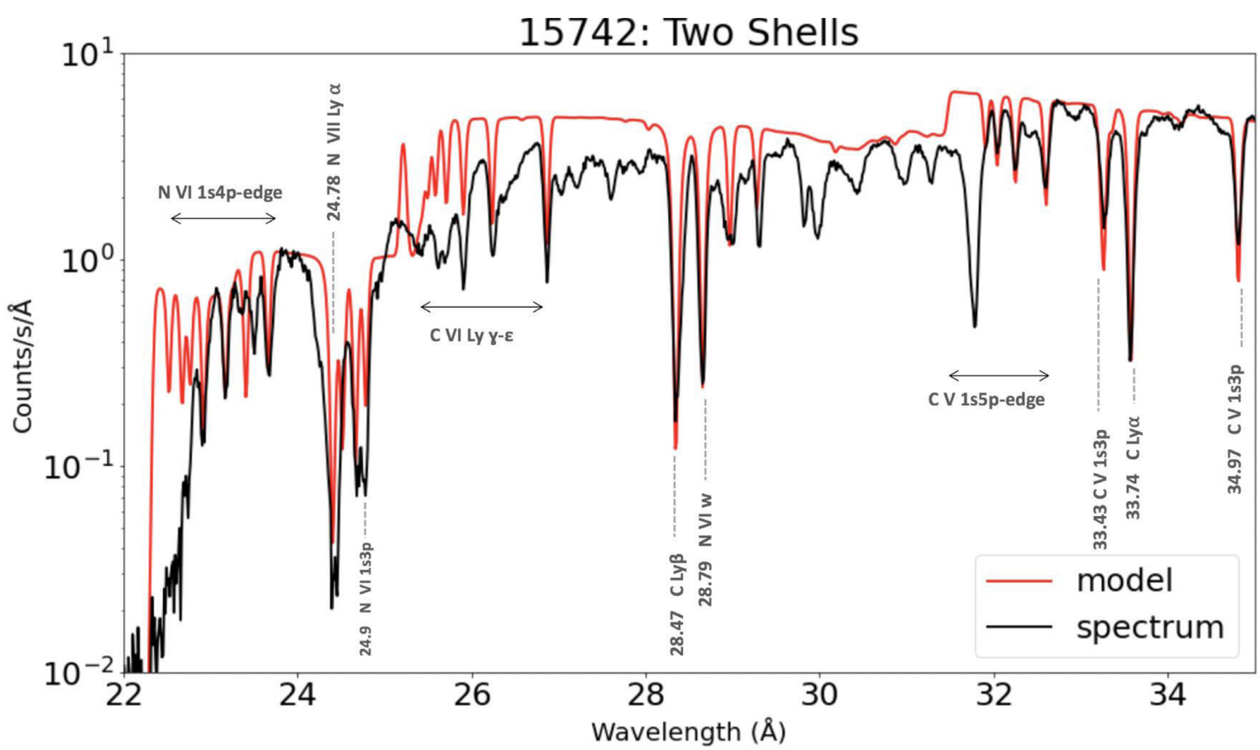


Figure 1: *Model fit to spectrum of Nova Delphini 2013 (ObsID 15742), assuming a 6.3×10^5 K photosphere surrounded by two shells of absorbing material with temperatures of approximately 1.6×10^6 K. These shells have blueshifted velocities of 1300 and 4000 km/s, with the second shell having a much higher N/C abundance ratio than the first. This figure is adapted from Milla & Paerels (2023).*

pares them with other novae including V3890 (Ness et al. 2022), KT Eri 2009 (Pei et al. 2021), and LMC 2009a (Orio et al. 2021).

One of the main motivations in studying novae is to better understand how and which white dwarfs become supernovae, a process that depends on the balance between mass accretion gains and explosive losses. Observed features such as ejecta velocity, dispersal patterns, shell mass, metal enrichment, and nova recurrence rate can vary widely, with poorly understood dependencies on white dwarf mass, temperature, and binary mass transfer rate. Although many questions remain, LETG spectra are providing valuable glimpses of order amid the chaos. Hopes are high that the explosion of T Coronae Borealis (T CrB), eagerly expected later this year after a wait of 78 years, will answer a good number of those questions.

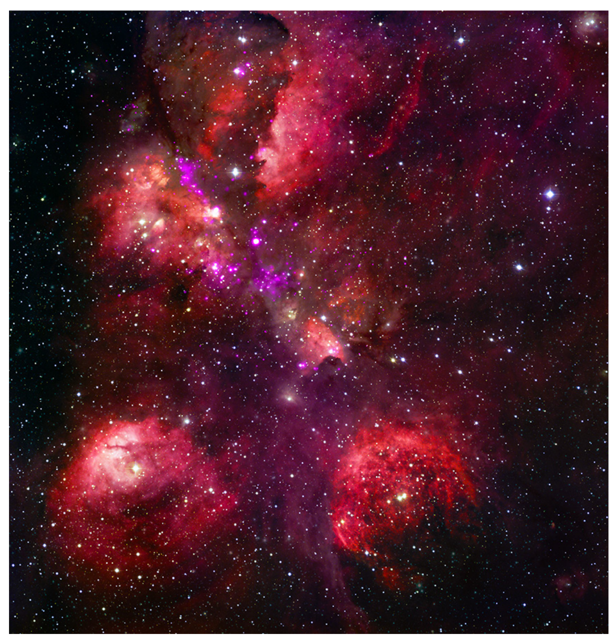
Facing Forward

Because of the steady loss of ACIS QE at low energies, the rate of non-calibration LETG/ACIS observations has declined (only two since May 2015), but the LETG/HRC-S wavelength coverage remains unchanged since the beginning of the mission. LETG also remains the only high-resolution X-ray observatory instrument able to observe energies below the C-K edge (0.28 keV, 44 Å), and good resolution can be achieved out to ~200 Angstroms using offset pointing. The LETG has provided unique capabilities in X-ray astronomy for a quarter century, and we look forward to more discoveries in the coming years.

References

Brinkman, A. C., Gunsing, C. J. T., Kaastra, J. S., et al. 2000, ApJL, 530, L111.
Fang, T., Marshall, H. L., Lee, J. C., Davis, D. S., & Canizares, C. R. 2002, ApJL, 572, L127.
Kovács, O. E., Bogdán, Á., Smith, R. K., Kraft, R. P., & Forman, W. R. 2019, ApJ, 872, 83.
Milla, J., & Paerels, F. 2023, ApJ, 943, 31.
Ness, J.-U., Beardmore, A. P., Bezak, P., et al. 2022, A&A, 658, A169.
Nicastro, F., Mathur, S., Elvis, M., et al. 2005, ApJ, 629, 700.
Orio, M., Dobrotka, A., Pinto, C., et al. 2021, MNRAS, 505, 3113.
Paerels, F., Brinkman, A. C., van der Meer, R. L. J., et al. 2001, ApJ, 546, 338.
Pei, S., Orio, M., Ness, J.-U., & Ospina, N. 2021, MNRAS, 507, 2073.
Rogantini, D., Costantini, E., Zeegers, S. T., et al. 2020, A&A, 641, A149.
Staunton, J., & Paerels, F. 2023, ApJ, 949, 26.
Valencic, L. A., & Smith, R. K. 2013, ApJ, 770, 22.
Wang, Q. D., Yao, Y., Tripp, T. M., et al. 2005, ApJ, 635, 386.
Williams, R. J., Mathur, S., Nicastro, F., & Elvis, M. 2007, ApJ, 665, 247.
Zappacosta, L., Nicastro, F., Maiolino, R., et al. 2010, ApJ, 717, 74.

The Cat's Paw Nebula (NGC 6334)



Credit: X-ray: NASA/SAO/CXC; Optical and H-alpha: ESO/MPG; Infrared: NASA/JPL-CalTech/Spitzer; Image Processing: J. Major

ACIS Update: Twenty-Five Years of Operations

Paul Plucinsky for the ACIS Operations Team

The Advanced CCD Imaging Spectrometer (ACIS) continues to function superbly, producing spectacular results over the past year. All ten CCDs are fully functional and all electronics are nominal, operating on the primary units. The ACIS flight software (SW) was updated on 19 September, 2023, to correct a bug that could lead to an infinite loop during the bias map computation in alternating exposure mode, to accurately report the state of the software in all cases after a safing action, to report more diagnostic information in the case of an unexpected condition, and to force a restart and reloading of the software if a front-end processor powered off unexpectedly. These updates will make ACIS more operationally robust and will help minimize any downtime for some anomalous conditions.

The space weather environment has become more active as the Sun approaches the peak of this Solar cycle. *Chandra* has interrupted the observing schedule six times from November 2023 through June 2024 due to high radiation levels. Two of these radiation safing events were triggered by the monitor in the ACIS flight SW called “txings.” The first of these txings triggers represents the first such event since the algorithm was modified in August 2022.

As of this writing, ACIS has performed over 29,000 science runs in the mission. Typically there is one science run per observation, so this is approximately the number of observations ACIS has executed, including calibration and diagnostic runs. As most *Chandra* users know, ACIS is an incredibly flexible instrument with many parameters that define the instrument configuration. *Chandra* users can tailor these parameters to select the active CCDs, clocking mode, event telemetry format, spatial region, energy range, and time resolution most appropriate for their science goals. To date 1,552 unique ACIS configurations have been created over the mission, most to optimize the science of the General Observers (GOs). All indications are that ACIS is capable of producing more spectacular results for many years.

Of course, these impressive accomplishments do not happen by accident. They are the result of the diligent efforts of a dedicated group of people who work within the *Chandra* Science Operations Team (SOT) and Flight Operations Team (FOT) at SAO, MIT, and Northrop Grumman (NG). The ACIS Operations Team (AOT) has been responsible for ensuring the health and safety and proper configuration and operation of the instrument since launch. The makeup of the team has changed over the mission, but the dedication to the successful operation of ACIS has remained constant. As we celebrate twenty-five years of discovery with *Chandra*, it is appropriate to recognize the efforts of the engineers and scientists who have made ACIS the tremendous success that is today by reminiscing about a few memorable moments in the mission.

The ACIS Door Anomaly and Opening in Orbit

There were many exciting “once in a mission” moments in the Summer of 1999, starting with the launch of *Chandra* on the Space Shuttle Columbia. The first such event for ACIS occurred while *Chandra* was still in the shuttle cargo bay before the satellite had been deployed. We needed to power-on ACIS to open the “little vent valve” in order to prevent water from accumulating on the focal plane. After deployment, a major milestone was the first diagnostic runs with all 10 CCDs demonstrating that they had survived launch. These crucial, first-time events are too numerous to describe in this article, but one activity deserves more reflection: the opening of the ACIS door. The ACIS door opening was already a critical event on the *Chandra* orbital activation timeline, but it became an even higher profile event after the door mechanism experienced a failure during ground testing. This failure occurred on the last day of the spacecraft thermal vacuum testing at TRW (now NG), and, with *Chandra* nominally four months from launch, it represented a major crisis for the *Chandra* project. The Science Instrument Module (SIM) had to be removed from the spacecraft, ACIS removed from the SIM, the door mechanism replaced, tested, and demonstrated to work, ACIS then had to be installed on the SIM, and the SIM installed on the spacecraft again. After this work had been completed, the spacecraft functional tests had to be repeated. Remarkably, all of this work was done within six months and *Chandra* was ready to ship to the Cape for launch thanks to the extraordinary efforts of the technicians and engineers at Martin Marietta (MM), Ball Aerospace, and TRW.

Unfortunately, the cause of the door mechanism failure was never determined (Podgorski, Tice, & Plucinsky 2000 and Kahan et al. 2001); there were several plausible ideas, but none could be proven with any certainty. Thus, there was significant anxiety in the project as the day approached to open the door, knowing that the cause had never been identified and the success of the *Chandra* mission depended on the door opening. Neil Tice was the engineer at MM who was responsible for the design of the door mechanism. Neil was confident that the door would open as planned and wanted to be with us in the control room for this critical activity. We developed a conservative procedure for opening the door that would operate the mechanism in stages, as opposed to opening the door in one step. This approach would allow the behavior of the mechanism to be verified after each step, offering us the possibility to pause or stop the procedure if unexpected behavior was observed. Our plan was to operate the mechanism five times, and only after the fifth activation should the door have been completely open.

The door opening activity commenced on 8 August, 1999, during the day shift (*Chandra* operations were 24-hours-a-day so soon after launch). On that day, there was a significant crowd of interested observers in the ACIS operations room—which we affectionately referred to as the "ACIS Chapel," since the room was a converted coat closet attached to the Technical Support Team room in the Hampshire Street Operations Control Center. The operations team for this activity included Neil Tice (MM), Ed Bougahn (the MIT engineer tasked with the responsibility for the flight operation of the door mechanism), Andy Northrup (the FOT engineer tasked with developing the flight procedure and products), and myself as the SOT ACIS lead, in addition to the FOT & SOT members who were controlling and monitoring the spacecraft. The key component of the door mechanism is a paraffin actuator, in which the paraffin is heated and expands, thereby doing work on a linkage that rotates a shaft to open the door. It was this paraffin actuator that was discovered to have failed in the ground testing.

The first operation of the mechanism on-orbit was designed to power on the heater to begin heating the wax, but to then turn the heater off before any motion of the door would be initiated. The heater was turned on for 90 seconds in this first step and the maximum temperature of the paraffin matched pre-flight expectations, but, as expected, no motion of the door was observed. This first step ensured that the commands worked, that the electrical connections to the actuator were still intact after launch, and that the paraffin was behaving as it had in ground tests. After the wax had cooled back to its original temperature, the next step was to turn the heater on for 110 seconds. During this heating cycle, the wax reached a temperature at which it was expected to begin to rotate the shaft to open the door. We observed that the angle of the door with respect to the ACIS camera body had increased from zero to ~11 degrees. This was a crucial result as we now knew that the mechanism was working and had overcome any stiction between the O-ring and the top of the camera body. But the door was only open 11 degrees—we had more work to do!

The next cycle lasted 125 seconds and the door angle increased to 19.5 degrees: an encouraging result, but still far from what we needed for a successful mission. The fourth cycle lasted 140 seconds, and the door angle increased to 36.5 degrees. At this point, we were confident the mechanism was working, but we did not have a fully open door that would allow X-rays from the High-Resolution Mirror Assembly (HRMA) to reach the ACIS focal plane (FP). We were so close, but not there yet. The fifth cycle lasted 200 seconds, and when it finished the door angle had reached the fully open position. After two intense hours, the operations team could relax and the entire *Chandra* team could celebrate: the ACIS door was now open. Neil was right, the door mechanism worked as expected. *Chandra* and ACIS would see "first light" a few days later on 12 August, 1999, when the HRMA Sunshade door was opened and we discovered Leon X-1.

Commissioning and Discovery of Soft Proton Damage

The ACIS activation and checkout activities proceeded rapidly after the door was opened. The flight SW was updated to the latest patch version, all instrument modes were verified, and all functional tests were completed. The instrument was performing flawlessly, and the quality of the data was excellent. Now the exciting work of using ACIS with the finest X-ray telescope ever constructed could begin. As the calibration program to characterize the performance of the HRMA+ACIS system started, the team was delighted that all of the hard work of the previous years had culminated in a successful activation on-orbit.

However, on Labor Day weekend of 1999, it was recognized that the performance of the frontside-illuminated (FI) CCDs was signifi-

Figure 1: *ACIS Chapel during the door opening on 8 August, 1999. From left to right Neil Tice (MM), Ed Bougahn (MIT), Paul Plucinsky (SAO), Mark Bautz (ACIS-PS,MIT), Andy Northrup (NG), and Gordon Garmire (ACIS-PI, PSU).*

Figure 2: *ACIS Team in the ACIS Chapel, Fall 1999. From left to right Paul Plucinsky (SAO), Dimitrios Athens (MIT), Mark Bautz (MIT), Royce Buehler (MIT, seated), Peter Ford (MIT), George Ricker (MIT), Catherine Grant (MIT), and Bev LaMarr (MIT, seated).*

cantly worse than both what it had been just a few weeks earlier when the door was closed and what had been measured before launch. The backside-illuminated CCDs did not exhibit any degradation, a result that was puzzling at the time—but that provided a clue as to the cause. This discovery sparked a massive effort by the entire *Chandra* team to understand the origin of the degradation. Within a matter of weeks, it was determined that protons with energies around 100 keV were reflecting off of the HRMA surfaces with sufficient efficiency and propagating to the FP (Kolodziejczak et al. 2000). These protons penetrated deep enough in the FI CCDs to damage the buried channel region near the FI surface (Prigozhin et al. 2000a,2000b), resulting in an increase in the charge-transfer inefficiency (CTI).

The intensity of these soft protons was highest when *Chandra* transited the radiation belts and during Solar storms. It was determined that the best course of action was to translate the SIM every radiation belt passage and during severe Solar storms to move ACIS out of the focus of the HRMA (O'Dell et al. 2003). These operational changes were implemented in early October 1999 and have been executed every orbit since then. The AOT worked long hours from September to December to characterize the current performance of the CCDs, to experiment with alternate clocking sequences to mitigate the effect of CTI, and to understand the structure of the radiation belts to better protect ACIS. Once these operational changes were implemented, the rate of CTI increase reduced to the low value expected before launch. By the holiday season of 1999, the crisis had abated and operations returned to a more normal schedule. We were all relieved that the instrument performance had stabilized and looked forward to the nominal science phase of the mission.

A prime responsibility of the AOT has been to ensure that every command load for *Chandra* properly safes ACIS for the radiation belt transit (Virani et al. 2002 and DePasquale et al. 2002). In addition, the AOT and SOT carefully monitor the Solar weather and take appropriate actions to safe ACIS during severe storms (such as the historic storm in May 2024). These efforts continue to this day and have minimized the CTI increase to tolerable levels, enabling ACIS to continue to produce valuable data after twenty-five years in orbit.

Contamination

The next major challenge for ACIS operations and the calibration team was the discovery of the decrease in the low energy sensitivity in early 2002 (Plucinsky et al. 2003). This led to another large effort by the *Chandra* project to understand the cause of the degradation. It was determined that a layer of a mostly hydrocarbon contaminant with some oxygen and fluorine was accumulating on the ACIS optical-blocking filter (OBF; Marshall et al. 2003). The ACIS instrument had been designed to "bakeout" the instrument to remove such a contamination layer. The bakeout conceived before launch would raise the FP temperature from −120 °C to +30 °C and raise the camera body temperature from −60 °C to +25 °C. The MIT ACIS team conducted ground experiments that showed that the CTI of the FI CCDs would increase significantly if the detectors were to be warmed from −120 °C to +30 °C (Grant et al. 2005), which were consistent with the flight experience in which the CTI of the FI CCDs increased when the FP temperature was increased to +30 °C. Therefore, a new bakeout scenario needed to be developed which kept the FP temperature below −80 °C while also making the OBF as warm as possible to drive off the contaminants.

Such a scenario was developed (Plucinsky et al. 2004) with detailed thermal modeling from Neil Tice. The efficacy of such a bakeout was modeled (O'Dell et al. 2005, 2017) and found to depend sensitively on the volatility of the contaminant. If the contaminant has a high volatility, a bakeout to these temperatures would remove most or all of the contaminant, but if

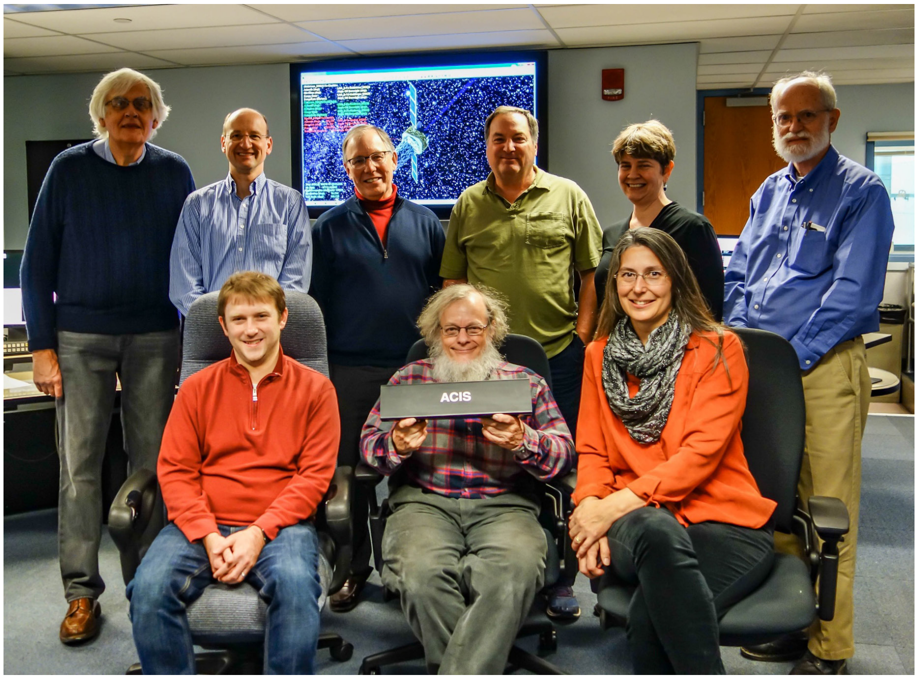


Figure 3: *ACIS Operations Team October 2018 in the Hampshire St. OCC soon before the move to the Wayside OCC*

Left to Right, Back Row: Peter Ford (MIT), Paul Plucinsky (SAO), Mark Bautz (MIT), Gregg Germain (SAO), Catherine Grant (MIT), Richard Edgar (SAO), Front Row: John ZuHone (SAO), Royce Buehler (MIT), Bev LaMarr (MIT)

the volatility is low, little or none of the contaminant would be removed. Given the uncertainty on the outcome of the bakeout and the potential risk to the OBF and the CCDs, the *Chandra* project decided not to proceed with a bakeout. The AOT spent considerable effort in studying a bakeout and developing an operational scenario to achieve the desired conditions for the bakeout, but once the cause was understood and the additional absorption could be modeled accurately, the crisis had ended and the AOT could return to nominal operations.

The radiation damage early in the mission and the contamination issue represented the most serious challenges to ACIS operations; however as the mission has progressed, the ever-increasing temperatures of the ACIS electronics and FP have required the most attention from the AOT. A multi-pronged approach has been adopted that allows ACIS to continue to deliver breakthrough science while ensuring the instrument remains within safe operating temperatures. The steps that have been adopted are limiting the length of a single observation at a given solar pitch angle, reducing the number of operational CCDs, and specifying different temperature limits depending on the science objectives of a particular observation. These strategies have been highly successful at maintaining the high observing efficiency of *Chandra* and ACIS and providing the highest quality data to the *Chandra* observers. The AOT will continue to employ these strategies in the coming years to maintain the spectacular results from ACIS.

A Change of Venue

A major event in the history of *Chandra* was the move of the Operations Control Center (OCC) from the Hampshire St. facility in Cambridge to the Wayside facility in Burlington. This transition took several years to plan and was executed in 2019. This move produced a tremendous amount of work for the *Chandra* Ground Operations Team (GOT) to first configure, populate, and test the new OCC, and then to maintain two OCCs until operations could transition to the Wayside facility for good. The Hampshire St. facility had the unique advantage for the AOT that most of the ACIS engineering team was located in the same building, one floor below the OCC. This proximity made meetings and the support of real-time activities especially convenient for the MIT staff. The AOT is of course depen-

Figure 4: *ACIS Operations Team at the Wayside OCC for the flight SW patch activity in September 2023*

First row: closest to the camera to farthest from the camera, Jim Francis (MIT), Jack Steiner (SAO), John ZuHone (SAO), Gregg Germain (SAO). Second row: Paul Plucinsky (SAO), Ken Gage (NG). Not shown: Catherine Grant (MIT), Mark Bautz (MIT)

dent upon the *Chandra* GOT for all of the infrastructure that makes the OCC work, but the AOT team is responsible for maintaining machines in the OCC that are used to support real-time activities with ACIS, such as recovery from anomalies and flight SW patches. We were quite comfortable in our home at Hampshire St. for the first 19 years of the mission, so the move was undertaken with some sadness. Nevertheless, new ACIS machines were purchased, configured, and installed in the new *Chandra* OCC at Wayside. The AOT had full functionality at the new OCC from the first day of operations at that facility thanks to the hard work of many people on the *Chandra* project. The facility has supported several ACIS realtime activities with the same level of support as the old OCC, most notable among these being the last two ACIS flight SW patch activities in August 2022 and September 2023. The Wayside OCC stands prepared to support any ACIS realtime activities on short notice.

ACIS has explored the X-ray universe for twenty-five years, fundamentally changing our understanding of astrophysics in many areas. It has been a great pleasure working on ACIS, but what has truly made the experience wonderful are all the people who have dedicated themselves to make ACIS the success that it is. It has been an honor and a privilege to work with this exceptional group of individuals. We look forward to continuing ACIS operations for many years in the future!

References

DePasquale, J. M., Virani, S. N., & Plucinsky, P. P. 2002, Proc. SPIE, 4844, 454.

Grant, C. E., LaMarr, B., Prigozhin, G. Y., et al. 2008, Proc. SPIE, 7021, 702119.

Kahan, M. A., Tice, N. L., Podgorski, W. A., Plucinsky, P. P., & Doyle, K. B. 2001, Proc. SPIE, 4198, 186.

Kolodziejczak, J. J., Elsner, R. F., Austin, R. A., & O'Dell, S. L. 2000, Proc. SPIE, 4140, 135.

Marshall, H. L., Tennant, A., Grant, C. E., et al. 2004, Proc. SPIE, 5165, 497.

O'Dell, S. L., Blackwell, W. C., Cameron, R. A., et al. 2003, Proc. SPIE, 4851, 77.

O'Dell, S. L., Swartz, D. A., Plucinsky, P. P., et al. 2005, Proc. SPIE, 5898, 313.

O'Dell, S. L., Swartz, D. A., Tice, N.W., et al. 2017. Proc. SPIE. 10397.

Podgorski, W.P., Tice, N.W., & Plucinsky, P.P. 2000, AMS, 34, 15.

Plucinsky, P. P., O'Dell, S. L., Tice, N. W., et al. 2004, Proc. SPIE, 5488, 251.

Plucinsky, P. P., Schulz, N. S., Marshall, H. L., et al. 2003, Proc. SPIE, 4851, 89.

Prigozhin, G. Y., Kissel, S. E., Bautz, M. W., et al. 2000a, Proc. SPIE, 4012, 720.

Prigozhin, G. Y., Kissel, S. E., Bautz, M. W., et al. 2000b, Proc. SPIE, 4140, 123.

Virani, S. N., Ford, P. G., DePasquale, J. M., & Plucinsky, P. P. 2002, Proc. SPIE, 4844, 464.

HRC Update

Grant Tremblay, Ralph Kraft, Dan Patnaude, Gerrit Schellenberger, Tom Gauron, & Paul Nulsen

Amid looming celebrations for *Chandra*'s 25th launch anniversary, the HRC Team is delighted to report that the instrument is performing nominally in our new operations paradigm and continuing to enable cutting-edge science as the highest resolution X-ray imager in history. Since its return to science with the "A-side" electronics bus on April 10, 2023, the HRC has successfully completed more than 250 observations for a combined total of more than 2.06 megaseconds of exposure time. The A-side anomalies of 2020 (which mirrored the B-side anomaly of 2022) have not returned, all data is of exquisite quality, and the HRC team remains maximally vigilant over all aspects of the instrument. Recall that, following the first A-side anomaly and power reset in August 2020, the voltage collapse reappeared after only 11 hours of operation, leading many to worry that the A-side electronics were permanently unusable for science (hence why we swapped to the B-side, thinking we would never return to the A-side). That we have now successfully used the A-side for more than 570 hours of observation without anomaly recurrence is a testament to the hard work of the entire *Chandra* Flight and Science Operations Teams and strong evidence in support of our new operations paradigm, which is designed to keep the instrument cool.

We now excitedly await new science results enabled by the HRC's return to work. Indeed, this Cycle, members of the global community are using the HRC's soft-end sensitivity to better understand a "valve-like" black hole feedback effect in a nearby elliptical galaxy, while others are using the HRC timing mode's hyperfine temporal resolution to observe pulsating neutron stars in M28. Meanwhile, a team recently used the HRC's uniquely sharp angular resolution to discover the first evidence of tidally induced activity in a brown dwarf. With community demand for the instrument remaining stable and high, the HRC is ready to continue enabling world-class *Chandra* science for years to come.

In light of this happy news, and with a sober cognizance of *Chandra*'s uncertain budgetary horizon, we are grateful and reflective of the twenty-five year legacy of this extraordinary instrument—and the people who brought it to life. This reflection is especially poignant given the recent passing of our dear friend, Jerry Austin. Jerry, in his forty years of service to SAO and as a globally recognized leader in the nascent field of X-ray instrumentation, was Lead Systems Engineer on the HRC from Phase B through its assembly, integration, testing, launch, and commissioning, remaining so over decades of operations. We hope that you will take time to read the article on Jerry in this issue of the newsletter, as well as this fascinating AIP Oral History interview with Jerry and Steve Murray, the HRC's original Principal Investigator. For a longer but fascinating story of the final, harrowing days of HRC assembly, we highly recommend reading Chapter 21 of *Revealing the Universe: The Making of the Chandra X-ray Observatory*, by Wallace and Karen Tucker.

Finally, we celebrated a bittersweet moment this Spring when our friend, Dr. Paul Nulsen, retired and moved away to be closer to his family in Australia. Paul was a core member of the HRC team for more than a decade, a mentor to so many at the Center for Astrophysics, and a brilliant scientist who has greatly advanced our understanding of galaxy evolution. Paul retains the ability to consult with

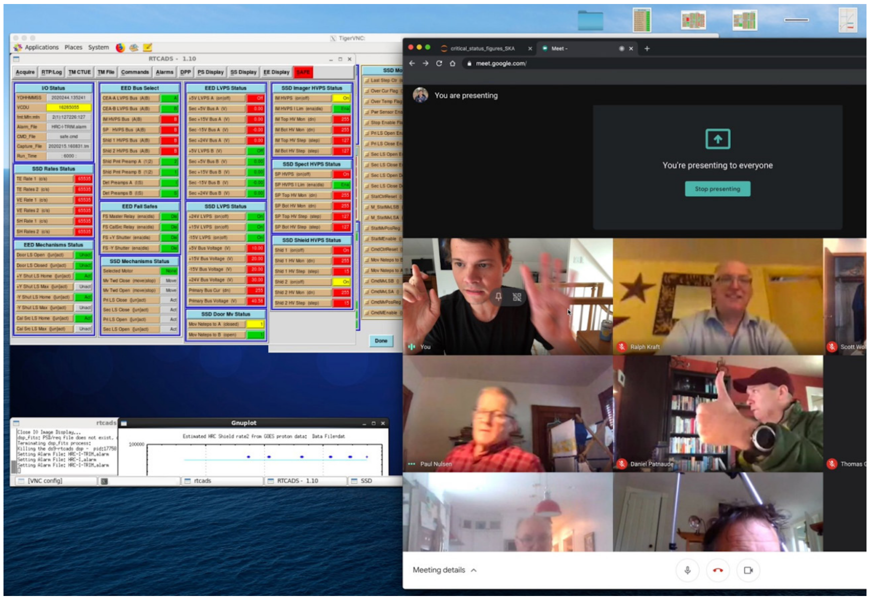


Figure 1: *Even long into his well-deserved retirement, Jerry remained a fierce intellect and the top expert on every intricacy of the HRC, which he helped build. Jerry even rejoined the HRC team to assist us with planning and execution of our anomaly response. The screenshot above is from August 31, 2020, when the HRC Team (alongside Jerry, bottom left) swapped the instrument to B-side electronics. Our team was connected to the flight comms loop with a skeleton crew in the control room, due to COVID lockdowns. Swapping to B-side electronics required the physical movement of four relay switches that had never been moved in orbit, after twenty-one years of exposure to the space environment. While we had full confidence in the engineering of the spacecraft, this was considered a risky spacecraft intervention. Jerry never doubted that the switches would flip. They did.*

Figure 2: *This Spring, we wished a happy retirement to our beloved friend and HRC Team member, Dr. Paul Nulsen (along with Dr. Susan Nulsen, who was a dear member of our team in spirit). While this was immensely bittersweet, we're still in frequent contact with Paul and Susan and planning visits to Australia soon. We're also delighted to welcome Dr. Gerrit Schellenberger to our group, who has been hard at work making our operations more robust and vigilant.*

Figure 3: A montage of the many people who have brought HRC to life and supported its operation for decades.

SAO should any HRC issues arise in the future, so we have not lost Paul's immense knowledge of the instrument for good. Meanwhile, the HRC team is delighted to have welcomed Dr. Gerrit Schellenberger to our group. Even with just a few months on the job, Gerrit has made incredible contributions to the team, including a robust new suite of instrument monitoring codes. The team is as strong as ever, and we're all actively planning to visit Australia as soon as possible to enjoy laughs and memories with Paul.

And so we close in the spirit of gratitude, reflection, and optimism for a continued bright future for *Chandra* and the HRC. Our community is proof that observatories and space telescopes are not just collections of metal and glass and silicon, or bytes of data on a hard disk. They are *human* endeavors, from dream to flight to discovery. We wish the global *Chandra* community a happy 25th launch anniversary, and close with hopes that its greatest discoveries lie ahead.

Overview of *Chandra* Calibration

Larry David

The CXC Calibration Team is responsible for monitoring the performance of the High Resolution Mirror Assembly (HRMA), the Advanced CCD Imaging Spectrometer (ACIS), the High Resolution Camera (HRC), and the Low and High Energy Transmission Gratings (LETG and HETG, respectively). This has been accomplished through an extensive calibration program that includes periodic observations of several standard X-ray candles (e.g., HZ43, SNR G21.5-0.9, E0102-72.3, and Abell 1795) as well as collecting data from the ACIS External Calibration Source (ECS).

HRMA

At launch, all calibration products were derived from ground-based measurements. The mirrors and gratings have required the fewest refinements to their calibration, and these corrections are applied to all data taken over the course of the mission. Only the detectors have time-dependent calibration products. The primary adjustment to the HRMA effective area occurred in 2009, when it was determined that the surfaces of the mirrors were covered with a thin layer of molecular contaminant. Periodic on-axis observations of AR Lac with the HRC-I have shown that the imaging properties of the HRMA have remained stable.

Transmission Gratings

The primary targets used to calibrate and monitor the performance of the gratings are HZ43 (a white dwarf), Mkn 421 (a blazar), and Capella (a chromospherically-active stellar binary). Since Mkn 421 is a variable source, interleaved observations with different detector/grating combinations have been carried out at periodic intervals to cross-calibrate between the gratings. No in-flight data have shown the need to adjust the 1st order transmission efficiency of the LETG. The most recent adjustments to the 1st order transmission efficiencies of the HETG were completed in 2009 to maintain consistency with changes to the HRMA effective area.

Since the LETG orders cannot be separated with the HRC-S, the higher order transmission efficiencies of the LETG must be calibrated using ACIS-S/LETG data. A sample of LETG/ACIS-S observations of bright continuum sources was used to refine the transmission efficiencies of the LETG higher orders in 2011. A calibration project is currently underway to refine the higher order transmission efficiencies of the HETG. Periodic observations of Capella have shown that the dispersion relation and Line Spread Function (LSF) of the LETG and HETG have remained stable.

ACIS

The response of the ACIS detectors has been affected by radiation damage, the build-up of contamination on the optical blocking filters, and an increase in focal plane temperature. Immediately after launch, ACIS suffered radiation damage by soft protons during passages through the Earth's radiation belts. Since October 1999, ACIS has been stowed during belt passages to prevent further damage. While ACIS is in a stowed position, it is illuminated by the ECS; data from the ECS have been heavily used to monitor the ACIS detectors. However, the ECS is a ^{55}Fe source with a half-life of 2.7 yr, and it is of limited use at the present time.

To correct for the effects of radiation damage, a CTI correction algorithm was developed and released to the public early in the mission. Recently, an updated temperature-dependent CTI correction file was released to the public in CALDB 4.11.1, improving the CTI correction up to a focal plane temperature of −105 °C. The recent improvements in the ACIS CTI correction allow for higher S/N observations at warmer focal plane temperatures.

ACIS observations of astronomical sources and the ECS have shown that molecular contamination has been building up on the optical blocking filters since launch. The uncontaminated ACIS QE is still based on ground-based flat field measurements. All time-dependent effective area corrections are made relative to the ground calibration. Early in the mission, the depth of the contaminant was monitored using line ratios in the ECS data, but the low energy lines eventually became too heavily absorbed to serve as a useful diagnostic tool. Since that time, periodic observations of the rich cluster Abell 1795 and "Big Dither" LETG/ACIS-S observations of Mkn 421 have been used to monitor the build-up of contamination. An ACIS contamination model was developed early in the mission, but changes in the composition and build-up rate of the contaminant have necessitated updates to the contamination model on a roughly yearly time scale. However, both the composition and build-up rate of the contaminant have remained fairly stable over the past five years.

The ACIS gain has shown a slow and steady decline over the course of the mission, with some dependence on the solar cycle. All time-dependent gain corrections are made relative to the ACIS gain measured during the first three months following the instrument cooling to −120 °C (January–March 2000). For most of the mission, time-dependent changes to the ACIS gain were calibrated with the ECS. As the ECS continued to fade, it became necessary to transfer the gain calibration to the supernova remnant Cas A and the Perseus cluster of galaxies.

HRC

The gain and QE of the HRC detectors have been monitored with periodic observations of the white dwarf HZ43 (a soft X-ray source) and the supernova remnant G21.5-09 (a harder X-ray source). These observations have shown a steady decline in the gain and QE of the HRC detectors over time. To remedy this situation, the high voltage (HV) of the HRC-S was increased in 2012 and the HV of both the HRC-S and HRC-I was increased in 2021. The 2021 HV increase restored the HRC detectors to their operating state of approximately three years prior. Another HV increase for both HRC detectors was recently performed in summer of 2024. Updated QE files have been released on an annual cadence to account for changes in the QE and HV, and new HRC QE tables will be released shortly, following the recent HV increase.

NGC 3532

Credit: X-ray: NASA/CXC/SAO; Optical: ESO; Image Processing: NASA/CXC/SAO/J. Major

NGC 7469

Credit: X-ray: NASA/CXC/Xiamen Univ./X. Xu; Optical/Infrared: NASA/ESA/UVA, NRAO, SUNY at Stony Brook/A. S. Evans, Hubble Heritage–ESA/Hubble Collaboration; Infrared: NASA/ESA/CSA/L. Armus, A. S. Evans; Image Processing: NASA/CXC/SAO/J. Major

Chandra X-ray Center (CXC) Manager's Report

Mark Weber

Reporting period: November 2023–May 2024

Now in its 25th year, the *Chandra* X-ray Observatory continues its highly successful science mission. With its unique capabilities for sub-arcsecond X-ray imaging and high-resolution X-ray spectroscopy, *Chandra* carries out essential observations for many leading X-ray and multi-wavelength investigations in current astrophysical research.

Chandra observing time continues to be highly sought after. Scientists worldwide responded to *Chandra*'s Cycle 25 call for proposals with 408 proposals requesting 4.9 times the total available observing time. The dual-anonymous peer review held in June of 2023 approved 103 observing proposals and 21 archive and theory proposals.

The *Chandra* Observatory continues to function at or near pre-launch expectations. Incremental changes in the performance of some components continue, generally in line with pre-launch predictions and without hindering operations. The performance of the spacecraft's thermal insulation continues to decline gradually; however, this trend has been mitigated by careful mission scheduling, aided by increasingly sophisticated software scheduling tools. The gradual accumulation of molecular contamination on the UV filter that protects the ACIS detector reduces ACIS's sensitivity to low-energy (below ~1.5 keV) X-rays. *Chandra* continues to maintain its observing efficiency near the mission-long average of ~70%. (To protect its instruments, *Chandra* cannot observe during passages through Earth's radiation belts; spacecraft maneuvers, instrument setup, and other procedures necessarily take up a small part of the remaining available time.)

NASA has instructed the *Chandra* Observatory program (as well as the *Hubble* Space Telescope program) to take part in an Operating Paradigm Change Review aimed at evaluating the potential science return that could be provided with substantially reduced budgets using revised mission operation models. The *Chandra* program submitted its information package in April and presented its operational options to the review panel in May.

The *Chandra* Press Office has been active in issuing image releases, science press releases, and other communications of *Chandra* research results. A complete listing of *Chandra* press releases is available at http://chandra.harvard.edu/press.

The approach of *Chandra*'s 25th anniversary in July prompts a look back at the evolution of the program's management. NASA's Marshall Space Flight Center in Huntsville, Alabama, oversees the *Chandra* program. In 1991, as the result of a competitive procurement, NASA awarded a contract for the *Chandra* X-ray Center (CXC; then the AXAF Science Center) to the Smithsonian Astrophysical Observatory (SAO) to carry out the scientific functions for *Chandra*, including soliciting proposals, processing, archiving, and distributing scientific data, and supporting the scientific community. Several years later, NASA determined that science activities and mission operations would be conducted most efficiently if combined within a single organization and expanded the scope of the CXC to include *Chandra* mission operations. The CXC was also given responsibility for administering the *Chandra* grants program. The CXC carries out all functions of the program, from soliciting proposals, planning observations, and operating the spacecraft and instruments to receiving, processing, and delivering data, calibrating the instruments, and supporting the science community with data analysis software, scientific conferences, and NASA research grants.

The *Chandra* management structure, which closely integrates all aspects of the mission, has proven to be highly effective, and it has remained unchanged through significant changes in staffing levels. Since launch, the total number of staff—including MSFC, SAO and subcontractor personnel—has decreased by approximately 42%, in spite of increasing operational challenges due to component aging. Even with fewer staff, the CXC has provided increased levels of utility for the scientific community, such as the innovative *Chandra* Source Catalog and enhanced functionality and support for the CIAO data analysis software. Maintaining such performance despite the staffing decrease was accomplished by introducing efficiencies and automation in many areas of the CXC. In 2015 an expert panel reviewed *Chandra* spacecraft operations and determined that the staff level was at approximately the minimum required for a mission of this size and complexity. The 2022 Senior Review of NASA operating missions gave the *Chandra* program its highest rating, "Excellent."

The *Chandra* Project looks forward to celebrating *Chandra*'s 25th anniversary with a science symposium this December in Boston and with other events during the year, as well as to many more years of productive scientific discovery.

Chandra Data System Software — A Retrospective Look

Janet Evans for the CXCDS Software team (Past and Present)

A System Overview

The *Chandra* X-ray Center Data System (CXCDS) software provides the end-to-end software support for *Chandra* mission operations (Fig. 1). The team developed, maintains, and supports the software that drive most of the CXC-based forward (proposer to spacecraft) and return (spacecraft to observer) threads necessary to perform the *Chandra* observing program (for further details, see Evans et al. 2008).

The forward thread begins with proposal submission and receipt software that manages development, validation, and submission of

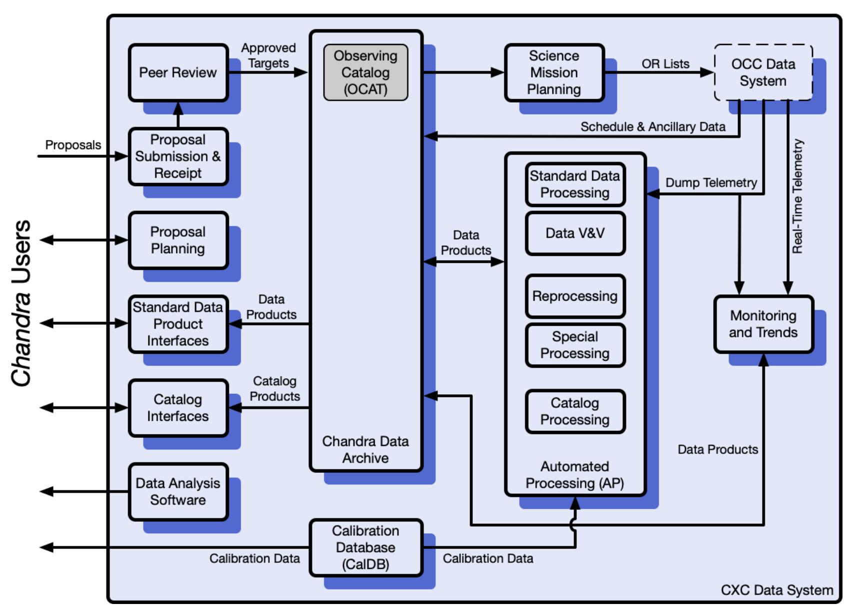


Figure 1: Schematic diagram of the CXC data system components and architecture. The CXCDS automated processing facility is co-located with Flight Operations at the OCC. The Chandra data archive is hosted at the same location and mirrored off site. Proposal submission and receipt, Science mission planning, and science user support are located at the SAO Garden Street location.

user science proposals and their receipt by the CXC. Additional software applications support the organization of peer review panels, assignment of reviewers to panels, conflict checking proposed observations, and managing peer review statistics and reviews. Approved targets are promoted to the observing catalog (OCAT) database in preparation for science mission planning. Mission planning software extracts observations from the OCAT and supports assignment of these observations to weekly schedules in a way that satisfies scheduling constraints stated in the proposals. The resulting observation request (OR) list is submitted to the *Chandra* Operations Control Center (OCC) for detailed scheduling and command generation. The OCC returns the detailed observing plan, which is compared to the request to validate the schedule.

Receipt of dump telemetry data from the OCC begins the return thread. Standard data processing (SDP) pipelines perform standard reductions to remove spacecraft and instrumental signatures and to produce calibrated data products suitable for science-specific analysis by the end user. Each pipeline includes ~5–30 separate programs, or tools, and several dozen pipelines comprise the SDP thread. Processing is managed by an automated processing (AP) system that monitors data, instantiates pipelines, monitors pipeline status, and alerts operations staff when anomalies occur. Information extracted from the OCAT is used to manage observation processing and to verify that the observation was obtained in accordance with the observer's specifications. At this stage, any data can be reprocessed as needed (e.g., because of prior errors or improved calibrations), and custom manual workarounds can be applied to any observation that requires special handling.

Monitoring and trends software performs limit monitoring of both dump and real-time telemetry for health-and-safety and triggers real-time alerts of anomalies as configured by the CXC Science Operations Team. Databases support long-term trends analysis to predict future spacecraft and instrument function for forward planning.

The *Chandra* Data Archive (CDA) securely stores all telemetry and data products created by SDP. Archive software restricts access to proprietary data, performs data distribution to observers, and manages public release of data once the proprietary period expires. Several interfaces to the CDA are supported to meet the needs of the various user communities for access to *Chandra* data. Chief among these interfaces to the CDA is ChaSeR, a flexible and powerful search and retrieval tool that meets the needs of professional users and incorporates authorized access to proprietary data. Similarly, CSCview is the premier interface to the *Chandra* Source Catalog (CSC), although CSC data can also be queried using a number of interfaces defined by and compliant with the International Virtual Observatory Alliance (IVOA).

The Calibration Database (CalDB) for *Chandra* is a HEASARC-compliant, software-accessible data structure that is used in both SDP and the *Chandra* Interactive Analysis of Observations (CIAO) data analysis software package.

The CIAO software package is the distributable data analysis system for *Chandra*, and all users of the observatory (internal, guest, and archival) utilize the package to perform further calibrations and science-specific analysis, as well as to extract publishable information from the pipeline data products. CIAO consists of an extensive set of analysis tools, including Sherpa—an integrated application for spectral and spatial modeling and fitting—and SAOImage DS9 for visualization. Some tools perform *Chandra* instrument-specific calibration and analysis functions, while others are designed to be compatible with a variety of missions while taking advantage of special knowledge of *Chandra* internals where appropriate.

Software design and development

Software development for the CXCDS began in the mid 1990s and continues to support the mission today. The system consists of ~2 million logical lines of code, including C/C++, Python, SQL, Java, Perl, and a few stray algorithms written in Fortran.

Early development of the system followed a formal systems engineering approach. CXC scientists and software engineers were partnered with an external contractor, TRW (now Northrop Grumman). Together, the CXC and TRW developed system and science requirements that were the basis of the design and implementation of an operational system that met the needs of the project and that was completed by launch.

The system delivered at launch was written for "normal," "steady" operations and assumed an integrated (all systems) telemetry stream as input. This was not the reality of Orbital Activation and Checkout, where one component is turned on at a time—so we had to improvise. To this day I tell folks that we made it, but also that we had to support 90 releases of the data system in 90 days to add flexibility and enhancements to meet the realities of the live data. A good software patch and deploy system is critical from the start. It took us a few months to meet the other major requirement, which was to process and deliver new observations in one week. It seemed like a huge requirement at the time, and we worked to estimate what was needed for hardware and what could be managed by software runtime to meet the deadline. After several months we had reached that goal. With the increased capabilities of hardware over the years and a robust data system, most *Chandra* observations are currently processed and delivered to the PI by operations within one day.

The design of the data system architecture was planned in detail to meet the needs of a project that was fairly complex and had many variables. The characteristics that guided the design were modularity, flexibility, compatibility, extensibility, and reuse of off-the-shelf software whenever possible.

The resulting CXC software system is highly modular and follows a layered architecture that consists of layers of software components and modules separated by standardized application programming interfaces (APIs). Each layer hides the details of its internal structure and mechanisms from the other layers. The CDA was fully integrated into the system from the start and fully supported all of the operations functions.

We also worked up front to address maintainability, performance, and, for some parts of the system, portability. So now with twenty-five years behind us, it's an interesting exercise to reflect on the maintenance and major migrations the system has undergone over the years.

25 Years in Operations

Originally developed on Solaris, the data system was migrated to Linux in 2002. Subsequently, in 2004 a second migration from a 32-bit-based system to a 64-bit-based system was implemented to match current hardware. The structured design and layered approach built into the system provided a solid foundation for these migrations. Migration to Python was also a fundamental upgrade to the system. Python wrapper scripts were built on C libraries to expose them to scripting interfaces (especially I/O libraries), and the science and software teams began writing many tools in Python that are used for operations—many of which are released in CIAO (as discussed in Issue 34). Currently underway, with a scheduled completion this fall, is a migration of the code base to GitLab from the original ClearCase configuration and release management system. We are also modernizing the software build infrastructure and testing framework that will bring the system more in sync with other astronomical systems today.

The *Chandra* data system has features that parallel more modern software trends, though implemented in a somewhat dated fashion reflecting the technology available in the mid to late '90s. For example, software "sharing" is a current topic in software circles, whereby two or more users or projects interactively work on the same library or application made available through Git for managing versions on the cloud. CXCDS/SW has engaged in software sharing through the use of Off-the-Shelf (OTS) software. We implemented software sharing using commercial OTS (e.g., Sybase for the Archive, Clearcase for configuration and release management), free OTS (e.g., HEASARC/cfitsio library for data file I/O), and adapted OTS (AOTS) that were imported and modified for *Chandra* needs (e.g., STScI *Hubble* pipeline processing system, GSFC proposal system). In all there are ~80 OTS packages that are managed in the CXCDS system reflecting a NASA requirement on the system to use OTS whenever possible to save on software development and cost.

Our *Chandra* data analysis package CIAO was developed to be downloaded and configured on the user's home computer. This seemed a big challenge in the early 2000's, but as systems have become more compatible over time, the challenge has become easier. In the early days, a scripted system managed the packaging and deployment of CIAO to various Linux platforms, while more recently a migration to a more standard Conda packaging system has been adopted.

The overall data system diagram has stayed mainly constant over the years. We have maintained the system and the content of each operational component to stay current with spacecraft changes, telemetry changes, proposal needs, data processing, monitoring and trends, archiving data products, user needs in CIAO and Sherpa, and the recent release of the *Chandra* Source Catalog 2.1.

Looking back on the past twenty-five years, the CXCDS system has served *Chandra* science operations well; the up front planning and design has paid off. The team has managed operational changes, OS upgrades, compiler and scripting language transitions, and many more changes over time that would not have been possible without the forward thinking and structural architecture designed from the beginning. We continue to meet the needs of the Observatory and are doing our part to contribute to the astrophysics discoveries of *Chandra*.

References

Evans, J. D., Evans, I. N., & Fabbiano, G. 2008, Proc. SPIE, 7019, 701917.

Cassiopeia A

Credit: X-ray: NASA/CXC/SAO; Infrared: NASA/ESA/CSA/STScI/D. Milisavljevic (Purdue Univ.), I. De Looze (UGent), T. Temim (Princeton Univ.); Image Processing: NASA/CXC/SAO/J. Schmidt, K. Arcand, and J. Major

The *Chandra* Bibliography through Data

Raffaele D'Abrusco, Erin Scott, and the Archive Operations team

The *Chandra* Data Archive (CDA) has tracked the scientific impact of the *Chandra* X-ray Observatory since its launch by collecting, classifying, and curating a comprehensive list of scientific and technical publications related to *Chandra*. Papers are automatically selected from an as-broad-as-possible pool of candidate publications available in the Astrophysical Data System (ADS) and classified by Data Processing and Archive Operations team experts. The candidate *Chandra* papers are labeled according to many criteria, including (but not limited to) the significance and type of usage of *Chandra* data, whether the publication is scientific or technical, and the specific *Chandra* observations and/or *Chandra* Source Catalog (CSC) data products used in the publication. The metadata collected for each paper included in the bibliography are recorded in databases and used to calculate a variety of metrics that rely both on *Chandra*-specific attributes and bibliographic properties of the publications (number of citations, whether they are refereed or not, etc.). A regularly updated selection of typical bibliographic metrics can be found here.

At the pinnacle of the hierarchy of *Chandra*-related publications included in our bibliography are the so-called *Chandra* Science Papers (CSPs): refereed papers where *Chandra* plays a pivotal role, i.e. publications that could have not been written if *Chandra* had not been operating. Recently, we classified the 10,000th CSP over the almost 25 years of operations of our mission. Understanding how CSPs use *Chandra* data sheds light on how the existence of the *Chandra* archive has affected the type of science performed; in what follows, we present some insights from our investigations of how CSPs relate to *Chandra* archival observations.

Data complexity

The building blocks of the *Chandra* archive are what we call "ObsIDs" (short for Observation ID), corresponding to an observation of a specified target for a specific proposal with a specific observational configuration. Single observations of *Chandra* targets can be—and often are—split into several ObsIDs based on observational requirements dictated by the scientific goals of the proposal they belong to or to facilitate their scheduling. The archive has grown to include ~23,000 single ObsIDs (among all categories of proposal including Calibration), covering ~4% of the area of the sky once and ~1.2% of the sky at least twice, with a variety of combinations of detectors and observational configurations. The linking of each paper to all ObsIDs it includes allows a granular mapping between bibliography and data holdings, which lends itself to measuring the "data complexity" of a typical *Chandra* publication.

The most obvious way to assess the complexity of *Chandra* data used in papers is by counting the number of ObsIDs used in publications. The histogram of the distribution of the number of ObsIDs linked to all CSPs classified so far (Figure 1) shows a lopsided distribution: ~90% of all CSPs use 50 ObsIDs or fewer, ~7% employ between 50 and 250 observations, and only the remaining 3% of papers are linked to a larger number of ObsIDs. The rapid decrease with increasing number of observations is interrupted by a spike in the 600–649 bin, corresponding to a handful of refereed papers (independently written by non-overlapping list of co-authors) that investigate different aspects of approximately the same sample of archival observations of galaxies and the clusters of galaxies they reside in. This is a curious example of the type of insights that can be gained from even the simplest analysis of the

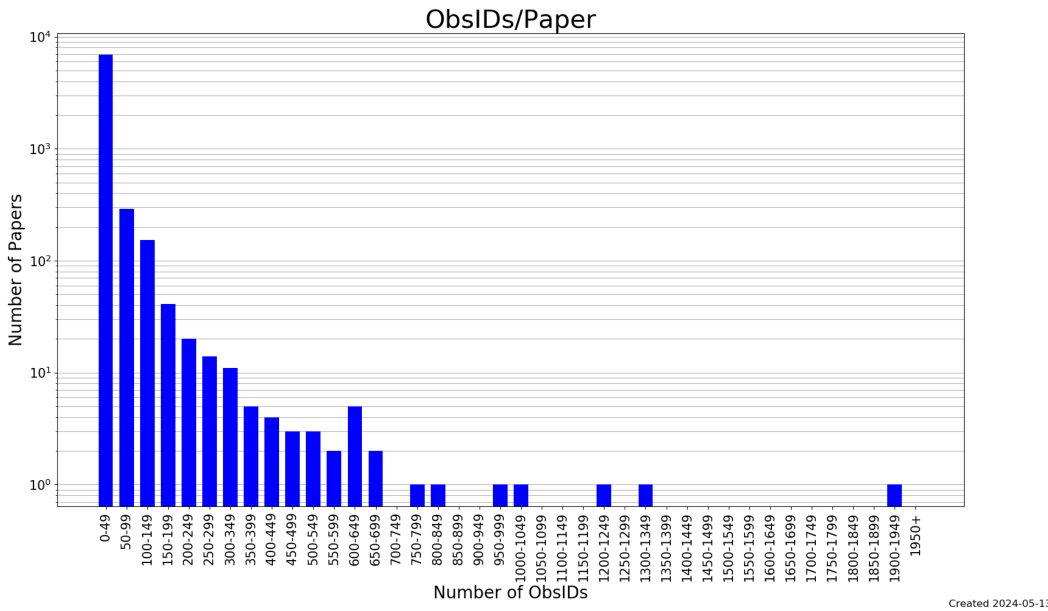


***Figure 1**: Histogram of the distribution of Chandra Science Papers (CSPs) as a function of the number of ObsIDs linked to the paper.*

bibliography data collected by the CDA. Conversely, the 7 CSPs linked to more than 700 ObsIDs offer an impressive picture of the diversity of astrophysical questions *Chandra* has helped to answer, as they span wildly different classes of astrophysical sources and research fields (from cataclysmic variables to quasars, from normal galaxies to galaxy clusters, and culminating with cosmology).

Although interesting, a static picture of data–literature linkage does not illuminate the potential evolution of data practices in the *Chandra* community over time. The number of ObsIDs linked to papers as a function of the paper's publication year (Figure 2), on the other hand, has been slowly increasing from 1–2 in the first few years of the mission to ~5 in the past decade. A more marked increase is visible for the 3rd quartile of the distribution, which has grown to include 20 ObsIDs for 2024 publications (although data for 2024 are incomplete). The median length of single observations has remained relatively constant over the years from 2000 to 2021, with the recent decrease mostly driven by the adoption of *Chandra* Cool Targets (CCTs), a new category of typically numerous and short observations of targets located in regions of the sky that offer thermal relief to the spacecraft. For this reason, the growing "data complexity" of papers published over the last years cannot be entirely attributed to single programs being split into a larger number of ObsIDs more frequently than in the past for thermal or scientific reasons. A similar trend of increasing complexity is also visible—although with different magnitude—for specific types of programs (GOs, GTOs, TOOs, and DDTs) and different size categories (like Very Large Proposals), suggesting that the trend is driven by the same dynamics affecting how programs of all types and scales are used in the scholarly literature. Similarly to the total number of ObsIDs, the total exposure of all observations used in CSPs has slowly grown over time (Figure 2, lower plot); the median total duration has reached ~200 ks for papers in 2024 from ~50 ks in 2005, and the interquartile range now spans the 50 ks to 750 ks interval, compared to 50–250 ks in 2005.

The coordinated growth of the number and total duration of the observations linked to CSPs clearly indicates that the data content of scientific literature using *Chandra* has become more complex with time. A likely explanation of this trend is that, over the lifetime

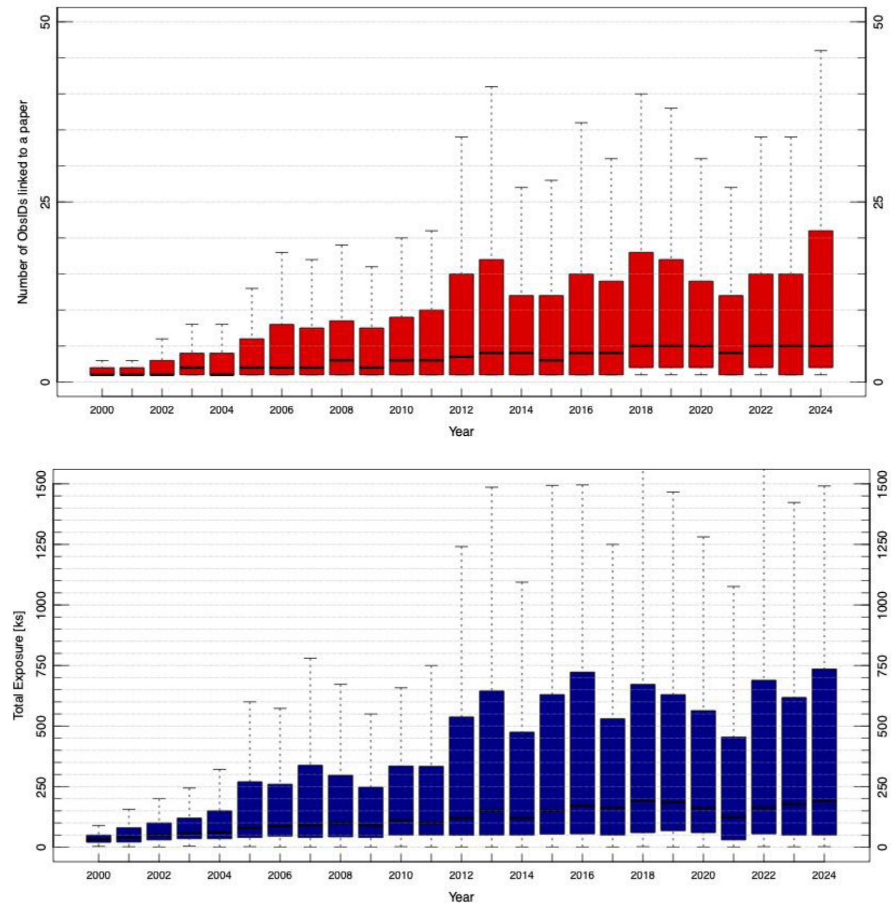


Figure 2: *Upper: Box plot of the distribution of the number of ObsIDs linked to CSPs as a function of the year of the publication. Lower: Box plot of the distribution of total exposure (measured in ks) used in CSPs as a function of the year of the publication.*

of the mission, the increasing availability of a growing mass of archival *Chandra* data has allowed scientists to focus on topics that require a large amount of freely reusable data, such as the time-dependent behavior of the same source observed multiple times, a comparative analysis of different sources of the same class, or the characterization of entire populations of astrophysical objects that can only be addressed via a statistical approach.

Archival science

The increase of the data complexity of *Chandra*-based publications hints at new venues for discovery being explored, but it only paints a partial picture of the importance of the archive as a multiplier of the total scientific production of the mission. The availability of large, well-curated, easily accessible public *Chandra* data has also expanded the community of astronomers who have produced scientific results using our mission. By comparing the list of authors of papers included in our bibliography with the Principal Investigators (PIs) and observers of approved *Chandra* programs, we have sorted CSPs into non-exclusive archival categories. Those papers using any data coming from programs whose key personnel are not among the papers' authors are labeled *mixed archival*, while papers where none of the *Chandra* data being used are connected with the authors are labeled *purely archival*. Using these definitions, we found that the fractions of fully archival and mixed archival CSPs have increased over the life of the mission to approximately 50% and 75%, respectively, of the total number of CSPs classified each year (Figure 3).

These results show the pervasive reach of

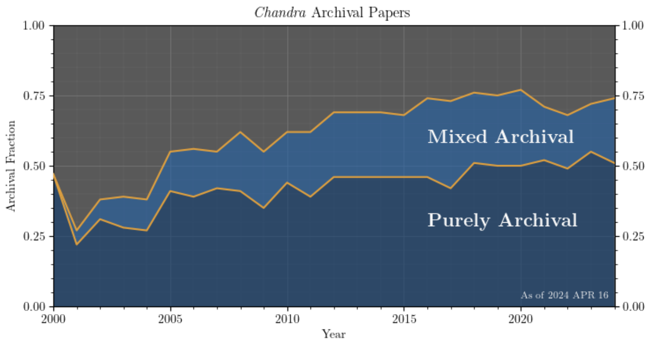


Figure 3: *Fractions of the total Chandra Science Papers that are classified as mixed archival (light blue) and purely archival (dark blue) over the life of the Chandra mission.*

Chandra archival data in the recent scientific literature and highlight the multiplicative effect of the accumulation of data on the potential for discovery. With half of all recent CSPs solely based on data with no author–proposer linkages, the archive has emerged as an equalizing force facilitating the fruition of the X-ray Universe well beyond the relatively small community of PIs and their teams. Even for the additional ~25% of mixed archival papers, where some analyzed observations are directly linked to proposals submitted by one or more coauthors, archival data have emerged as crucial components that complement and enrich the more recent non-archival data, thereby helping scientists interpret results and draw conclusions.

Conclusions

This article highlights how the granular data–literature linkages that the *Chandra* bibliography has collected since the beginning of the mission can be used to reconstruct the evolution of data usage habits in the community. While more analysis is required to confirm the underlying dynamics, the obvious increase in the complexity of the data typically used in *Chandra* papers suggests that scientists have harnessed the longevity of the mission by exploring areas of the discovery space that would have not been accessible without the progressive accumulation of publicly available data. These results are consistent with the known positive effects of well-curated archives on the total scientific output of large observatories (see Peek et al. 2019) and further confirm that the commitment to support comprehensive archives is key to fulfilling the discovery potential of missions like *Chandra*.

References

Peek, J., Desai, V., White, R. L., et al. 2019, BAAS, 51, 105.

Chandra Source Catalog — Release 2.1

Ian Evans and Rafael Martínez-Galarza for the *Chandra* Source Catalog team

Version 2.1 of the *Chandra* Source Catalog (CSC 2.1) was released to the community on April 2, 2024. By combining *Chandra*'s sub-arcsecond on-axis spatial resolution and low instrumental background with consistent data processing, the catalog provides carefully curated, high-quality, and uniformly calibrated and analyzed tabulated parameters (including positional, spatial, photometric, spectral, and temporal source properties) as well as science-ready X-ray data products. The sensitivity limit for compact sources in CSC 2.1 is unchanged at ~5 net counts (on-axis) for most observations. CSC 2.1 is an incremental release that adds imaging observations released publicly from 2015 through 2021 to the previous CSC 2.0 catalog version, increasing the overall size of the catalog by about 30%. Besides adding more recent observations, CSC 2.1 includes several enhancements that provide significant improvements over the previous release. In particular, the catalog is tied to the Gaia-CRF3 realization of the International Celestial Reference Frame for the best sky positions for catalog sources.

The catalog includes measured and derived properties for 407,806 unique compact and extended X-ray sources in the sky, allowing both statistical analysis of large samples as well as detailed studies of individual sources. Extracted properties are provided for 1,304,376 individual observation detections (2,143,847 when including photometric upper limits) identified in 15,533 *Chandra* ACIS and HRC-I imaging observations released publicly through the end of 2021 (see Figure 1). Photometric properties for 1,717 highly extended (≥30”) sources are provided, together with surface brightness polygons for several observation-specific contour levels. The total cumulative sky coverage of CSC 2.1 is 730.37 deg2, and multi-band limiting sensitivity is computed for the entire sky coverage of the catalog at a resolution of ~3.22 arcsec × 3.22 arcsec.

For each X-ray detection and source, the catalog provides a detailed set of more than 100 tabulated positional, spatial, photometric, spectral, and temporal properties (each with associated lower and upper confidence limits) measured in 5 energy bands for ACIS and a single energy band for HRC-I. As a result of this multiplexing, the catalog databases include approximately 1700 columns of information, split across several tables. Furthermore, a Bayesian aperture photometry code produces robust photometric probability density functions for all sources, even in crowded fields and for low count detections. Release 2.1 uses a Bayesian Blocks analysis to identify multiple observations of the same source that have similar multi-band photometric properties, and these observations are analyzed simultaneously to improve S/N.

The catalog contains roughly 40 different types of science-ready source- and field-based data products, totaling about 44 TB, including calibrated data files (photon event lists, multiband images, backgrounds, and exposure maps), derived measurements (position error Markov chain Monte Carlo draws, extended source contours, aperture photometry Bayesian marginalized posterior probability density functions, and Bayesian Blocks properties),

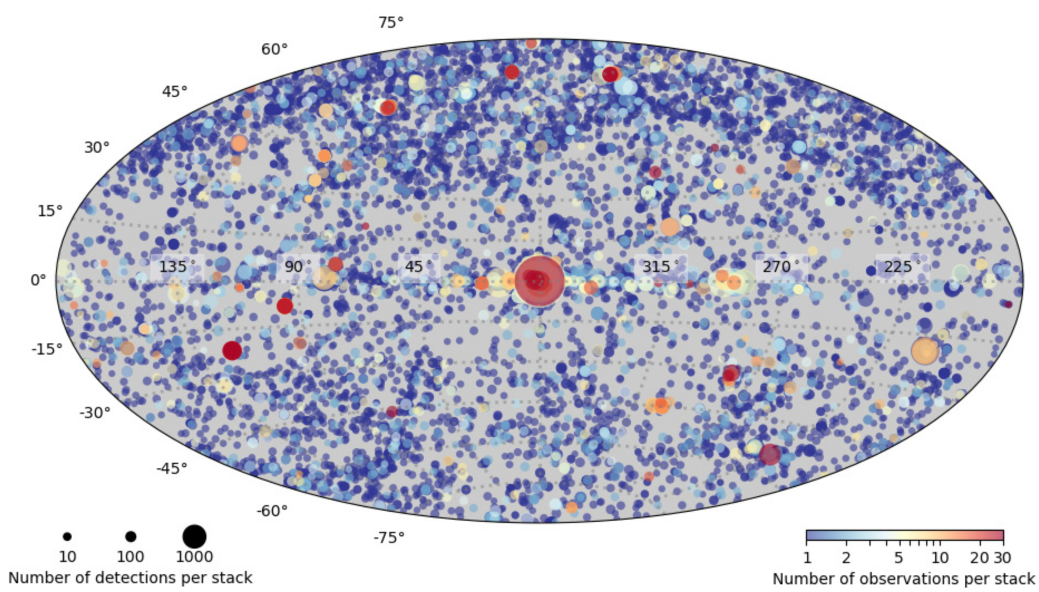


Figure 1. CSC 2.1 detections shown in Galactic coordinates, with the image vertically centered on the Galactic plane. Each circle represents an observation stack, with the color of the circle indicating the total number of observations included in the stack and the circle's size indicating the number of detections in each stack.

and data analysis products (PSFs, spectra, instrument responses, and light-curves). Since these data products are pre-computed by applying all of the appropriate calibration steps (*e.g.*, matching astrometry, merging observations, applying exposure corrections, removing background) included in the catalog pipelines, they can be used directly by the end-user to significantly simplify the effort required to perform detailed scientific analyses of properties for scientifically meaningful samples of sources without manipulating large volumes of data.

Data Access and User Interfaces

Data access and documentation for the catalog are available through the catalog website (cxc.cfa.harvard.edu/csc/). The catalog documentation describes the content and organization of the catalog data and the data processing steps, and the documentation includes detailed descriptions of the tabulated source and detection properties and data products. The What is new in CSC 2.1 update discusses the algorithmic improvements in CSC 2.1 compared to CSC 2.0. We suggest reviewing the Catalog Organization & Concepts page to make the most effective use of the catalog, while the Caveats and Limitations page provides important information about the catalog that should be reviewed by all users prior to using the catalog data.

Multiple user interfaces to the catalog are accessible via the catalog website's How to access CSC 2.1 page. The Quick Search web interface supports position-based and cross-match searches and returns a limited set of source properties, making it ideal for simple queries such as determining whether a source detected in another waveband has a *Chandra* X-ray counterpart. World Wide Telescope provides a visual interface based on the American Astronomical Society's World Wide Telescope that exposes the outlines of the stacked observations and the locations of the catalog sources, allowing the user to explore the sky coverage and content of the catalog. Clicking on a source in this tool brings up a box with a basic set of source properties.

For more sophisticated queries and to provide access to the full functionality of the catalog, we recommend using the CSCview application. CSCview is a downloadable Java application that allows arbitrary sets of tabulated properties to be retrieved based on combinations of user-specified constraints on any set of properties plus positional searches or cross-matches. These searches return tabulated results that may be saved to a file or SAMP'ed to another application. Catalog queries can be entered via a simple forms-based interface or alternatively via the ADQL query language. CSCview also provides options to retrieve any desired science-ready FITS data products.

Finally, there are several interfaces for users looking to integrate CSC 2.1 into their pre-established workflow. *Chandra*'s CIAO data analysis package includes a set of CIAO scripts to search the catalog via the catalog command-line interface. Additionally, Virtual Observatory interfaces that support the IVOA Simple Cone Search (SCS), Table Access Protocol (TAP), and Simple Image Access Protocol (SIAP) can access the corresponding catalog interfaces directly; web forms that allow queries via these interfaces are also provided. The Virtual Observatory interfaces allow Jupyter notebooks to access the catalog tables using the PyVO Python package.

A Historical Perspective

The provision of a catalog of X-ray sources identified by the *Chandra* X-ray Observatory was a requirement of the original NASA contract for the CXC. We started thinking about what such a catalog should include early in 2001 and had developed an initial catalog concept that separated detections and master sources (because of the variation of the size of the *Chandra* PSF across the field of view) a year later. Around the same time, we were considering whether, in addition to tables of measurements, the catalog should include "data objects" that could be used directly for further detailed analysis. These data objects later morphed into the now roughly 40 types of FITS data products (for compatibility with existing data analysis tools) that we supply as part of CSC 2.1. A couple of years later, we had developed a very preliminary prototype pipeline to perform source detection and other studies. While existing source detection algorithms could be manually fine-tuned for a specific field with a few iterations, the complexity here was to develop an approach that could robustly perform source detection on almost all observation fields irrespective of source content—and to do so with high detection efficiency, low false-source rate, and very minimal human intervention.

By late 2005 our source detection prototype was working sufficiently well, our catalog and pipeline concepts were settled, and other catalog pipeline prototype algorithms—such as aperture photometry—were coming together. In February 2006, we presented our plans to a well-qualified review committee of both X-ray and non-X-ray astronomers from across the globe. They provided outstanding feedback and had many excellent suggestions as to how to proceed. Our biggest takeaway from the committee was to ensure that the catalog was directly usable by multi-wavelength astronomers with little or no X-ray experience, while at the same time being sufficiently robust that X-ray astronomers familiar with *Chandra* data and state-of-the-art X-ray analysis techniques would feel comfortable using the catalog data. This advice caused us to reconsider and update the set of source properties that we were planning to include in the catalog to ensure that all our potential audiences would be well supported. The next two years saw us continuing to refine the catalog pipelines and fold in the changes that resulted from the feedback provided by the review committee. The first catalog production run commenced in September 2008, and Version 1.0 of the catalog, which included 94,676 X-ray sources from observations released publicly through the end of 2008, was released in March 2009. In August 2010, an incremental catalog release, CSC 1.1, was published, containing 106,586 sources from observations released publicly through the end of 2009.

Following release 1.0, we received tremendous feedback from the user community with numerous suggestions for future catalog releases. The three biggest limitations of release 1 were (a) source detection was performed on a single observation at a time, (b) the source detection threshold was relatively high, around 10 net counts on-axis, and (c) the source detection approach was unreliable in areas where the X-ray background was spatially variable (which resulted in regions around the cores of bright galaxies—often the most interesting region of the observation—being excluded). Release 2.0 was planned to address these issues and more. Multiple observations of the same field would be stacked (co-added) where possible prior to source detection, source detection would be modified to use multiple algorithms to identify candidate detections, and those detections would be graded using a maximum likelihood algorithm to achieve a lower detection threshold while still ensuring a low false-source rate. The changes required major updates for virtually all aspects of the production pipelines, and these updates required much longer than originally anticipated to develop and test. Release 2.0 production started in April 2015. While the initial stages of processing went well, by mid-autumn of 2015 we had amassed sufficient data to indicate that the maximum likelihood algorithm was providing unreliable detection positions for an excessive fraction of detections. Processing was suspended while we investigated the cause of this issue and developed a fix. Production restarted in

March 2016 and CSC 2.0 was finally released in October 2019, with 317,167 X-ray sources and ~1.4 million individual observation detections and photometric upper limits extracted from observations released publicly through the end of 2014. While the operational production schedule was impacted by multiple hardware and software issues, much of the delay resulted from the time required for manual quality assurance reviews that were designed to ensure a reliable catalog.

After the CSC 2.0 release, we immediately started working on a minimal set of updates necessary to add in more recent observations (accounting for the slow changes in the characteristics of the *Chandra* spacecraft and instruments that happen with age) while also dramatically reducing the number of manual quality assurance reviews compared to CSC 2.0. Version 2.1 of the CSC began production in April 2022. Completion of the release, announced above, brings us to the present day.

Enabling Science

The reason for the existence of the CSC is the science that it enables. The catalog constitutes a rich dataset that facilitates data-driven discovery, population studies, and detailed characterization of individual astrophysical sources. Some of the science highlights of the catalog include studies of the contribution of ultra-luminous X-ray galaxies to the ionizing radiation of galaxies, the identification of dual AGN and their properties as a function of pair separation, and the identification of transient events related to the merger of neutron stars. Release CSC 2.1 promises to bring along a new wave of discovery.

Celebrating 25 Years of CIAO: A Milestone in Astronomical Data Analysis

Antonella Fruscione, Douglas Burke, Catherine Cranmer, Kenny Glotfelty, Hans Moritz Günther, David P. Huenemoerder, William Joye, Nicholas P. Lee, Jonathan McDowell, Melania Nynka, David Principe, Aneta Siemiginowska

As we mark the 25th anniversary of the *Chandra* X-ray Observatory and of the *Chandra* Interactive Analysis of Observations (CIAO) software, we want to remember its long journey, celebrate its evolution from the beginning to the current version, and highlight some of its significant contributions to the field of X-ray astronomy. Since its inception, CIAO has evolved from a limited set of basic tools for data analysis and proposal preparation into a comprehensive suite of tools and applications that have empowered astronomers worldwide to dig deeper into astronomical data. Today's CIAO represents a culmination of decades of dedication and innovation in the field of astronomical data analysis.

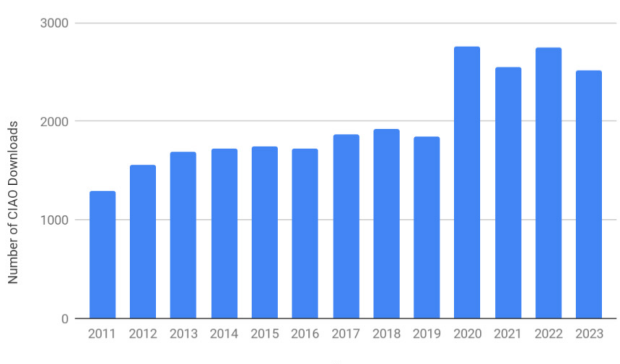


Figure 1: *Number of CIAO software downloads since 2011. CIAO has been downloaded thousands of times per year from all over the world. The spike in 2020 most likely represents the fact that users started to work from home on personal computers rather than institutional machines (where CIAO may be centrally downloaded).*

A Giant Leap in Capabilities

First released in October 1999, CIAO began as a modest package, available on only three platforms—Solaris 2.6, Redhat Linux 5.2, and Slackware Linux 3.5—and with a suite of around 30 tools designed to analyze data from the newly launched *Chandra* X-Ray Observatory (see our first CIAO newsletter article from 2000). Over the years, CIAO has transformed dramatically, keeping pace with technological advancements and the evolving needs of the astronomical community. The word "ciao" comes from an old greeting expression in the Venetian language, "s'ciavo," that means "I am your servant," and the name symbolizes the software's role in serving the astronomical community. This is a feat that, after a quarter century, we can claim we have accomplished!

Fast-forward to today, and CIAO 4.16 is a sophisticated, multi-platform software suite that includes over 150 tools and 100 contributed scripts and supports modern Linux and macOS operating systems. CIAO incorporates advanced data analysis features, makes extensive use of Jupyter notebooks, and has several components, like Sherpa and the contributed scripts, which are developed on Github in an open development model. SAOImageDS9, the premier visualization tool to display and analyze astronomical imaging data, is also distributed with CIAO.

Expanding Accessibility and Usability

Initially, CIAO was designed primarily for X-ray astronomers working on *Chandra* data. However, over the years, the software has evolved on many levels: for example tools have been updated both to respond to changes in *Chandra*'s operations or calibration as well as to support data and users beyond *Chandra* (reflecting its mission-independent design). CIAO has also become more accessible to a broader audience, including novice astronomers, students at various educational levels,

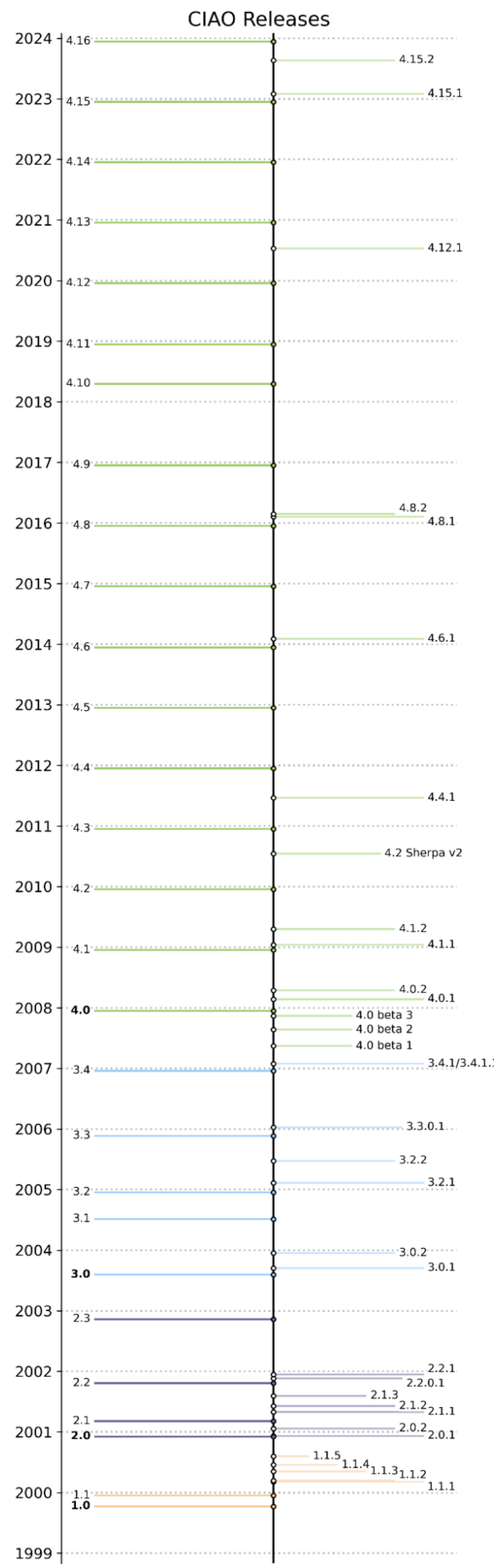


Figure 2: A timeline of CIAO releases from CIAO 1.0 (year 1999) to CIAO 4.16 (year 2023). Patch releases in between major releases are illustrated in the right section.

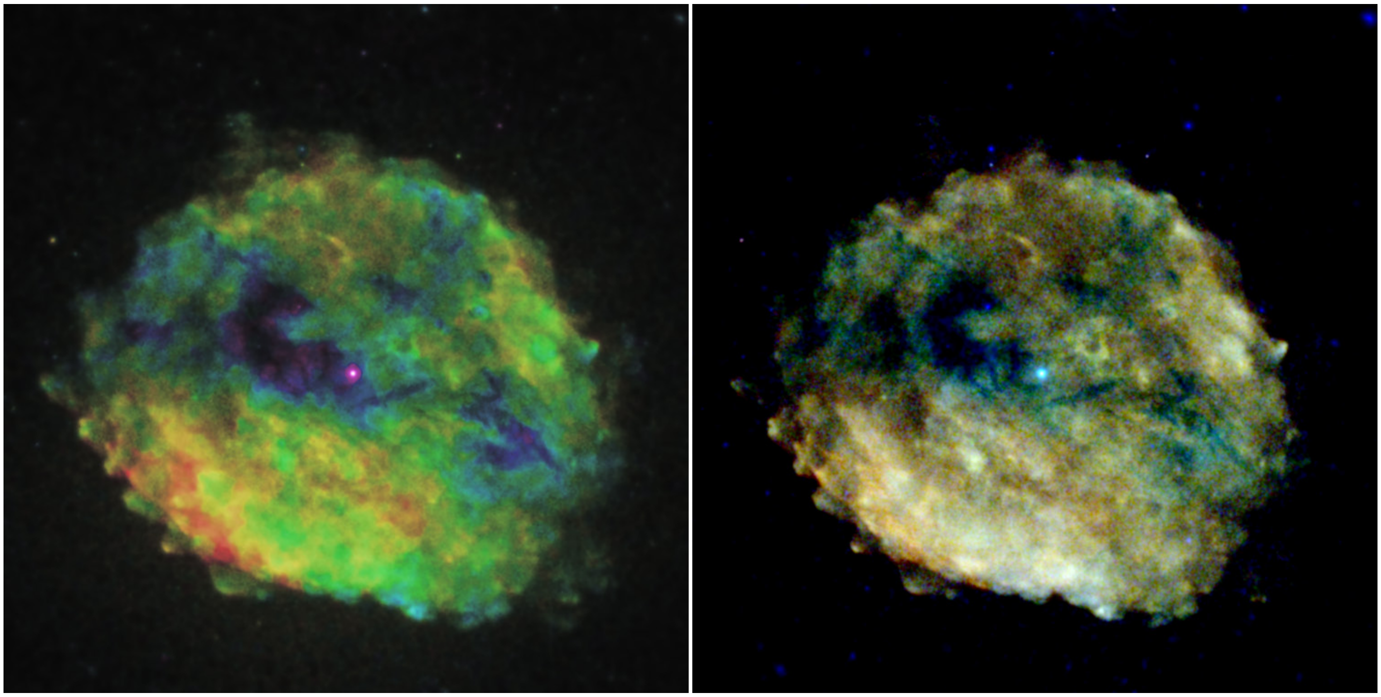


Figure 3: X-ray image of the supernova remnant RCW 103 using two methods of color representation: true color (left) and tri-color (right). The true color image was created using the new energy_hue_map script, which combines the adaptively smoothed counts image with the median energy at each location to create a true color image. Here, the color hues span a continuous range capped by red (median energies below 1.0 keV) and violet (median energies above 1.4 keV). The tri-color image was created using standard Chandra Source Catalog energy bands: soft (0.5–1.2 keV), medium (1.2–2.0 keV), and hard (2.0–7.0 keV). Traditional RGB tri-color images start by creating 3 images in separate energy bands, which are independently scaled to act as the individual color channels of the output image. The combination of primary colors (RGB) leads to the visual interpretation of secondary colors (eg. yellow, cyan etc.). True color images, in contrast, are created from a continuous energy range producing images in the "HSV" (Hue Saturation Value) color system.

and researchers from small and large institutions worldwide. This inclusivity has been facilitated by extensive documentation—designed to help non X-ray experts—and through 20 CIAO workshops held globally, which played a significant role in educating new generations of astronomers while also gathering valuable user feedback used to continually enhance the software and the documentation.

The CIAO workshops—which blend lectures and hands-on sessions to give real experience with *Chandra* data—began in 2001, attracting around 30 students per event to the Center for Astrophysics in Cambridge, Massachusetts. Over time, these workshops were extended to various conferences and institutions lacking local expertise, including one in 2017 in Pune, India, and a virtual workshop in 2020 during the Fifth Arab Astronomical Society School for Astrophysics in Egypt. These international experiences, in regions traditionally overlooked by Euro- and US-centric institutions, profoundly broadened the CIAO team's perspective and underscored the critical importance of extending support to institutions and users lacking the necessary infrastructure, support systems, and expertise to fully leverage the benefits of *Chandra*'s "free and open" data and software. For example, CIAO now includes scripts designed to handle data analysis even in low bandwidth situations.

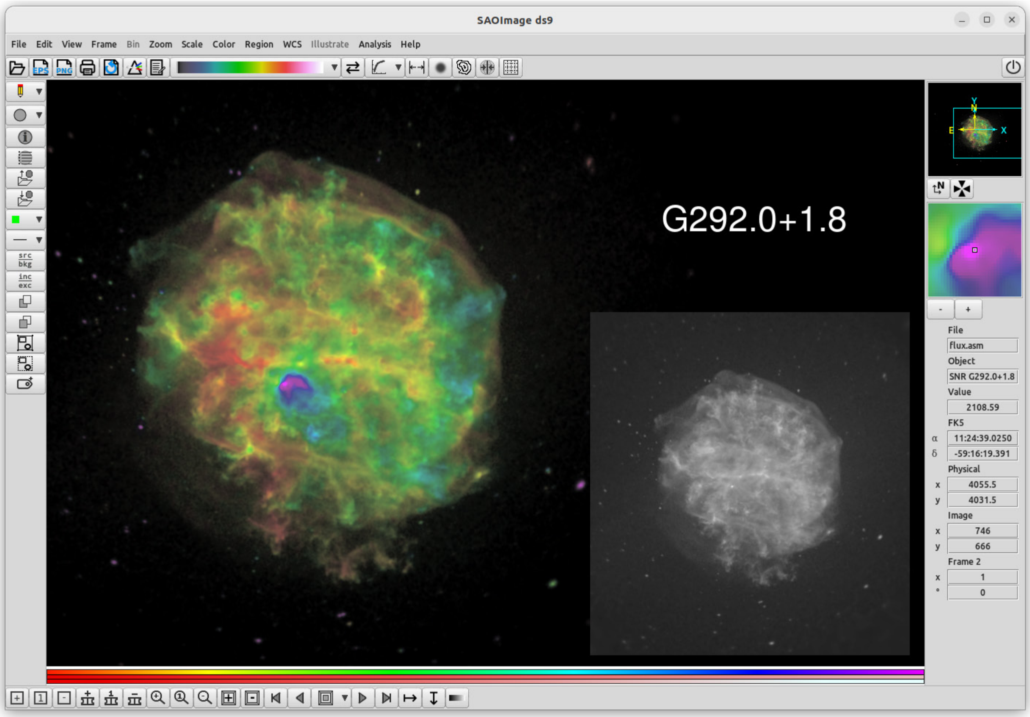


Figure 4: Chandra image of SNR G292.0+1.9 using the latest beta release of SAOImageDS9 v8.6b2, demonstrating some of the program's new features. In addition to long-term support for RGB frames, DS9 now supports HSV and HLS frames, such as shown here. The colors of this image represent median energies from 1.0 keV (red) to 1.5 keV (purple). The gray scale inset is a broad-band image created with DS9, saved in PNG format, and inserted into the frame using the recently added Illustrate mode. This mode allows images and graphics (text, circles, boxes, polygons) to be placed directly in the display. The DS9 window is shown using the new Advanced View layout (View -> Advanced).

Adapting to Technological Shifts

The journey of CIAO has seen significant technological shifts, even to some of its very core infrastructure. In the early 2000s, scripting in CIAO used the S-Lang scripting language; however, by 2008 Python became CIAO's primary scripting language, due to the latter's widespread adoption in the astronomical community and extensive documentation. This transition has not only modernized CIAO but also enhanced its capabilities, making it more versatile and user-friendly. The version 4.0 update that implemented this change also involved reviewing and rewriting the entire suite of contributed scripts to ensure consistency and maintainability. Moreover, some of the original and obsolete tools were dropped in favor of more modern tools, complex scripts, or applications. CIAO's Sherpa application, which is now available as a standalone Python package on GitHub, exemplifies the possibilities of an open-source collaboration and modern software practices.

Enhanced User Support and Documentation

The documentation, probably CIAO's crown jewel, has evolved significantly since 1999. What started as simple text files has grown to become a comprehensive list of data analysis threads and guides and, most recently, Jupyter notebooks. This impressive collection now encompasses over 2100 pages between CIAO and Sherpa, including more than 1160 help pages, 235 bug pages, 181 data analysis threads, 118 dictionary entries, and 101 FAQs, as well as various guides, caveats, galleries, "why" topics, and other written materials.

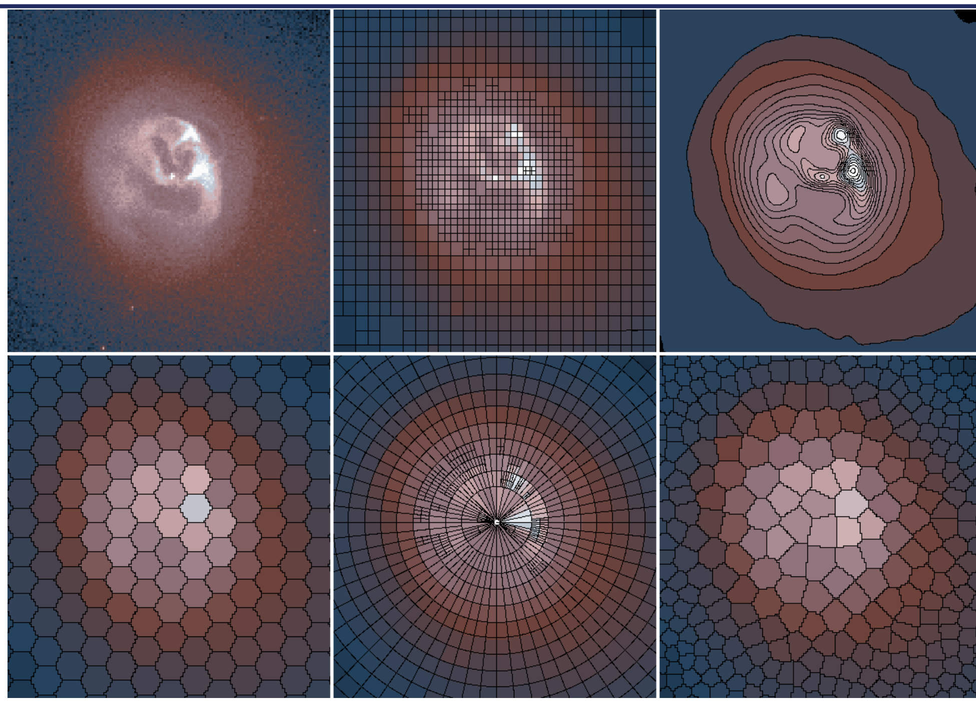


Figure 5: *Demonstration of some of the advanced adaptive/alternative binning tools available in CIAO. All images show a 620 ks observation of Abell 2052 in the 0.5–7.0 keV band. The left column shows uniform tilings: bins of squares (top, ~1″ on a side) and hexagons (bottom, side lengths of ~4″), the latter generated using the hexgrid tool. In the center column, the images are adaptively binned to have at least 900 counts per bin: rectilinearly (top) using dmnautilus and in polar coordinates (bottom) using dmradar. The right column shows more morphologically complex binning: a contour map (top) generated with dmcontour and mkregmap and a centroid map (bottom) produced by centroid_map, which is based on Voronoi tessellation of the local maxima in the image. Different binning methods can be especially useful when making products such as temperature maps or hardness ratio maps.*

The Jupyter notebooks provide an interactive environment where users can execute code and visualize results within the same document, making data analysis more intuitive and accessible. This addition represents a major step in making CIAO's powerful tools even more user-friendly.

A User-Driven Evolution

User support has always been a priority for CIAO. From the early days of ad hoc email support to the robust HelpDesk system today, CIAO has maintained a commitment to assisting its users promptly and effectively.

CIAO's journey has been characterized by a continuous exchange between its designers and the users. HelpDesk queries, user contributions, feedback from workshops, and the adoption of new technologies have all played crucial roles in shaping and reshaping the software. This need-driven evolution has allowed CIAO to remain an up-to-date software system for the wide multiwavelength astronomical community, capable of meeting the evolving demands of scientific research.

Celebrating Achievements and Looking Ahead

As we celebrate 25 years of CIAO, we know that its legacy will endure well past *Chandra*, having set a high standard for astronomical data analysis tools and documentation. It is important to recognize that CIAO is the product of a collective effort of a large community of users—software developers, scientists,

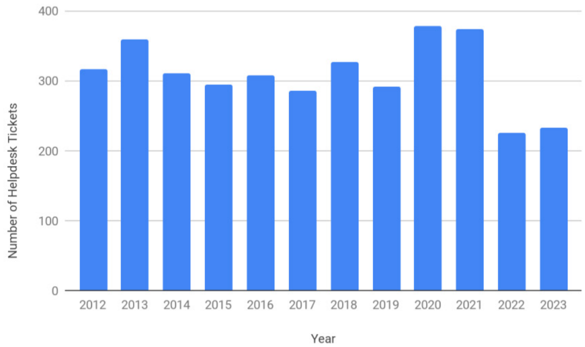


Figure 6: Number of Helpdesk tickets per year since 2012. Every year hundreds of questions are answered by CIAO experts, most within one day. Questions and answers contribute to the improvement of the software and the documentation.

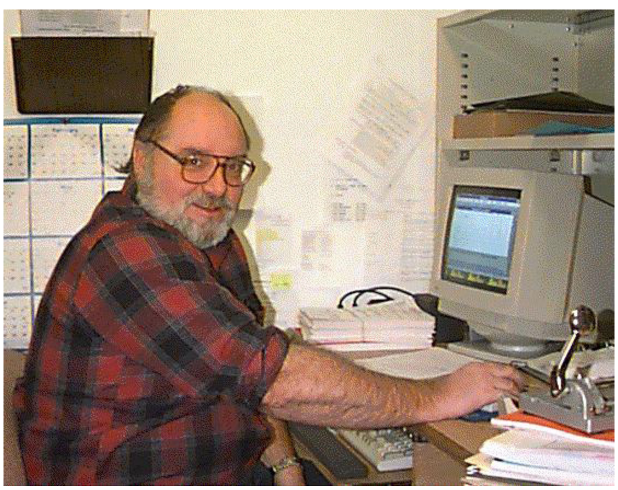
students—who all have contributed to CIAO's success in different ways. The software has become an indispensable tool for X-ray astronomers and beyond, facilitating groundbreaking discoveries and, in keeping with one of the grand challenges of the Smithsonian Institution, "unlocking the mysteries of the universe." CIAO is truly at the service of science!

Acknowledgments

CIAO has been a collaborative effort involving numerous *Chandra* X-ray Center (CXC) members—too many to list here—over the past 25 years, including members from the CXC Science Data Systems group at the Smithsonian Astrophysical Observatory (SAO) and Massachusetts Institute of Technology (MIT) and from the CXC Data Systems group at SAO. CIAO 4.16 builds on the many contributions and the many achievements along the way.

This work is funded by NASA Contract NAS8-03060, *Chandra* X-ray Center.

Gerald K. Austin (1940–2023)



Our colleague and friend Jerry Austin passed away on December 3, 2023, after an illness of several years. Jerry was born in Detroit, Michigan, and, after graduating from Michigan State University, Jerry came to the Boston area to study mechanical engineering at MIT. In the mid-1960's, he joined the X-ray astronomy group led by Riccardo Giacconi at American Science and Engineering (AS&E). From our perspective he never left the field or our X-ray astronomy team for the remainder of his years. We fully recognize that this brief article cannot possibly capture the breadth and depth of Jerry's enormous contributions to the field of X-ray astronomy. His work with colleagues and friends was a major factor in the tremendous growth and success of the Smithsonian Astrophysical Observatory (SAO) and the Center for Astrophysics (CfA) over the past 50 years. He was ever-present and often the unofficial overseer of many incredibly challenging and ultimately successful projects. His unassuming title in later years of General Engineer hardly begins to describe everything that he did—applying the range of skills and expertise he brought to every project—continuing even after his retirement in 2019.

One of us (HT) had the great fortune of starting his professional career at AS&E in 1968 working on the first NASA satellite dedicated to X-ray astronomy, for which Jerry soon became the lead mechanical engineer. When that satellite launched in December 1970, it was renamed Uhuru—Swahili for freedom—since it was launched just off the coast of Kenya on the 10th anniversary of Kenyan independence. Uhuru performed well beyond expectations, providing the first solid evidence for the existence of black holes, explaining how the bright X-ray sources in our Galaxy are powered, and discovering sources associated with "active galaxies" and clusters of galaxies. Simply stated, Jerry was integral to making those discoveries possible.

Soon afterwards, while still at AS&E, Jerry—along with Bruce Dias, Dave Boyd, Dick Goddard, Ed McLaughlin, Phil McKinnon, and Adrian Roy, among others—was instrumental in building the first X-ray mission with a true telescope: the HEAO-B, renamed the Einstein Telescope after launch in 1978. Following the integration of that payload, Jerry and the above-named engineers moved to SAO, joining the High Energy Astrophysics Division in 1977 to work more closely with Riccardo and the X-ray group there. Using the imaging power of the telescope and its cameras, the Einstein team demonstrated that essentially all classes of astronomical objects, ranging from nearby stars to distant quasars, radiate X-ray emission and constitute an essential channel for investigating and understanding how our universe works. It is fair to say that Jerry and his engineering colleagues were in the midst of every aspect of designing, building, and testing the Einstein science payload. No doubt, he knew more about that mission than anyone else. If, by chance, there was something he did not know, he knew where to get the information.

Following his work on the Einstein project, Jerry became heavily involved in the laboratory development of higher-performance, high resolution microchannel plate (MCP) X-ray imagers. He played a central role in demonstrating the capabilities of larger-format MCP detectors with higher quantum efficiency. These advancements during the 1980's were applied to the High Resolution Imager provided by SAO (through NASA) to the German-led ROSAT mission launched in 1990 (see more below).

Jerry's formal training was in mechanical engineering, but he was conversant in all engineering disciplines—mechanical, thermal, structural, electrical—required to bring complex projects together. He understood much of the physics of the detectors and their readouts and easily and regularly interacted with the scientists.

Jerry's crowning achievement within X-ray astronomy was his leadership and management for designing, building, calibrating, and integrating the High Resolution Camera (HRC) for the mission that would be named *Chandra* after its launch in July 1999. SAO's Steve Murray was the Principal Investigator (PI) for that instrument. Steve and Jerry worked incredibly closely on the HRC, starting from the technology phase in the 1980's and continuing for many years after the launch. After Steve's untimely passing in 2015, one of us (RK) assumed the role of HRC PI.

The HRC was designed and built at SAO in Cambridge, Massachusetts, during the first half of the 1990's. For reasons that we can truly no longer recall, Jerry was formally the Quality Control engineer on the HRC instrument team. To no one's surprise but to everyone's delight, Jerry was effectively the lead Systems Engineer and led the technical development of the flight hardware and its integration into the spacecraft. He was involved in every step of the design and the flight build. In particular, he personally performed the assembly of the flight MCP stack into the camera housing along with Steve Murray and SAO scientist Jon Chappell in the HRC clean room. He wore the clean room bunny suit quite well! The assembled flight model (FM) HRC was inserted into the X-ray vacuum pipe at SAO for testing and calibration, with Jerry overseeing this laboratory evaluation to ensure that all performance requirements were met.

The FM was then transported to the X-Ray Calibration Facility (XRCF) at Marshall Space

Flight Center (MSFC) in 1997 to perform a much more extensive calibration than could be done in the SAO lab. Tests at the XRCF verified the combined imaging performance of the High-Resolution Mirror Assembly (HRMA) with the HRC, as well as with the other *Chandra* science instruments. Jerry oversaw the safe transfer of the HRC to MSFC and its installation into the vacuum pipe at the XRCF. With the science team, he developed and tested all of the procedures for operation during the extensive ground calibration. The HRC was then transferred to Ball Aerospace in Boulder, Colorado, for integration onto *Chandra*'s Science Instrument Module (SIM)—the translation stage used to select the appropriate science instrument and to adjust the focus for a *Chandra* observation. Once mounted on the SIM, the HRC underwent several weeks of thermal/vacuum testing, with Jerry again supervising the testing, developing the procedures, confirming the performance, and ensuring the health and safety of the instrument.

The HRC on the SIM was next transported to the TRW facility in Redondo Beach, California, in 1998 for integration onto the spacecraft. The integrated *Chandra* payload then underwent months of thermal, environmental, and electrical testing, with the HRC again under Jerry's calm supervision. Once testing was complete, the observatory was shipped to Kennedy Space Center for installation in the Shuttle Columbia. Jerry and Steve were part of a small team who had the opportunity to board Columbia once *Chandra* was installed to manually release a valve before launch.

Chandra launched on July 23, 1999, with Jerry at KSC to witness the milestone.

After launch, Jerry quickly returned to the *Chandra* Operations Control Center (OCC) in Cambridge and was a central participant in the orbital activation of the HRC. He continued to play a key role monitoring the long-term health and safety of the flight instrument and approving adjustments deemed necessary. Sadly, his own health began to deteriorate several years ago, and a younger generation of scientists and engineers came on-board to continue operating the HRC. Yet even though he was retired, when unexpected power supply issues intermittently impaired and then halted operation of the HRC in mid-2022, Jerry continued to consult with the team. Eventually, the HRC team understood the problem and developed workarounds, enabling the resumption of high quality operations in April 2023—which are continuing as of July 2024.

Figure 2: Jerry Austin (seated left) and Steve Murray (standing left) with members of the testing team during thermal/vacuum testing at TRW in 1998.

Jerry handled the stress of playing such an important role on the HRC for nearly 3 decades with seeming ease. He always had an air of calm confidence even when things were chaotic. His approach was actually fairly simple: apply "Best Engineering Practices" in all cases and it would be hard to go wrong. He was ALWAYS prepared, no detail was too big or too small for him, and everyone trusted his judgment. Jerry was one of the few people that the HRC PI, Steve Murray, (and the three of us) would listen to without question! When Jerry said things should be done a certain way, that's how they got done.

For those interested in further details, there is a wonderful 1998 oral history involving Jerry Austin and Steve Murray covering their work on Uhuru, Einstein, ROSAT, and *Chandra*. The transcript can be found at:

https://www.aip.org/history-programs/niels-bohr-library/oral-histories/28614

In addition to technical and leadership roles for the X-ray projects described above, Jerry also took on a range of management and engineering roles for many CfA programs, first from within the High Energy Astrophysics Division and then after joining the Central Engineering Department in 2003. As already noted, he was lead engineer for the SAO development of the High Resolution Imager (based on the Einstein HRI) for the German-UK-US ROSAT mission launched in 1990. ROSAT carried out what was then the most-sensitive X-ray mapping of the entire sky in the 1990's. Jerry also applied his vast talents and unlimited energy to contribute substantially to the following instruments or missions: Skylab Apollo Telescope Mount S-054 X-ray telescope, Solar-B/Hinode X-Ray Telescope, Interface Region Imaging Spectrograph (IRIS), Stardust, Solar Dynamics Observatory Atmospheric Imaging Assembly, BepiColombo Strofio, and Parker Solar Probe Solar Wind Alphas and Protons (SWEAP) Investigation.

Within Central Engineering, Jerry wore many hats at various times, including Manager of Product Assurance, overseer for the transfer of critical documents from one storage facility to another, and a lead participant in the construction of the CfA's new engineering and instrumentation facility, starting from specification and design stages through contractor selection and on to oversight of the actual build. Jerry also served as acting Manager of Central Engineering when needed.

Jerry's diverse engineering background, vast problem-solving experience (which prevented several serious situations from occurring in major programs), tenacity, willingness to serve as a mentor for those at earlier career stages, penchant to volunteer for whatever organizational needs arose, extensive involvement with NASA (for which he received a number of awards), and overall role in blazing new trails in astronomy combine to illustrate the tremendous loss felt by so many of us. His experience at SAO was so varied and extensive that it would be impossible for even a team of people to fully appreciate, let alone replace. This loss speaks to how high he set the bar.

Figure 3: Jerry organizing a Central Engineering Tiger Team meeting.

Gerald Austin was a great engineer and a tremendous colleague, and he had an unforgettable influence on everyone who had the pleasure of working with him. He played an absolutely critical role in the development of X-ray astrophysics in the United States for more than 50 years, with contributions to many important missions—some still operating today. Many of the scientists in our community probably never met Jerry, but a large fraction have benefitted from his work. His role in the development of X-ray astronomy over five decades cannot be understated. Jerry's work has had a profound impact on multiple generations of scientists and engineers who will carry his legacy onward for decades into the future.

Prepared by Harvey Tananbaum, Ralph Kraft, and Melinda Dillon

Updates on the NASA Hubble Fellowship Program

Paul J. Green

The NASA Hubble Fellowship Program (NHFP) awards 24 postdoctoral prize fellowships each year and is one of the most coveted fellowships in astrophysics. NHFP fellows are awarded up to three years of funding to support research of their choosing. There are three "flavors" of NHFP fellow according to their science interests: Einstein, Hubble, and Sagan. These science flavors respectively correspond broadly to the questions:

1. How Does the Universe Work?
2. How Did We Get Here? And
3. Are We Alone?

The Science Leads for the NHFP are Andy Fruchter at STScI (for the Hubble), Dawn Gelino at NExScI (for the Sagan), and myself at the CXC (for the Einstein). Together, we administer the NHFP application and selection process, organize symposia, guide overall science policies, and support the ongoing productivity of the fellows.

NHFP Symposia

The NHFP hosts a symposium every year for fellows to share their scientific progress and plans, to get to know their peers, and to foster collaborations both in and beyond astrophysics. The 2023 NHFP symposium, which was sponsored by the *Chandra* X-ray Center, was held in Cambridge, MA, on September 18–22, near the Center for Astrophysics | Harvard & Smithsonian. Unlike most small astronomy meetings, any research topic is fair game, from sub-GeV dark matter detection to eclipse mapping of exoplanets to JWST imaging of galaxies at redshift 17. All the science sessions were live-streamed and recorded; videos have been made available by the *Chandra* X-ray Center.

At each symposium, we include a broad selection of non-science sessions for fellows only. This year, we hosted a career panel featuring discussions with Kim McLeod (Wellesley College), Francesca D'Arcangelo (MIT Lincoln Laboratory), and Monica Young (*Sky & Telescope*). There was a tour of Harvard's Great Refractor and artist Aura Satz presented her exhibition about the Harvard Plate Stacks. The STScI Grants division answered fellows' questions about grants and benefits. Saavik Ford (of ScienceBetter consulting) led a discussion about mentoring students. To wrap up the week was an incredible open mic session featuring rap, classical music, a demo of arxiv-GPT, and more.

The 2024 NHFP Symposium, in the planing stages now, will take place Sept 16–20, in the Cahill Center for Astronomy and Astrophysics at Caltech.

Selection of the 2024 NHFP Fellows

Each year, we post an announcement of opportunity in September for applications to the NHFP, with a deadline in early November. For fellowships starting in 2024, we received 521 complete applications for 24 postdoctoral positions. Of those, our selection process forwarded about 40% of applications to the 7 topical science panels for discussion. Finally, about 16% of those were sent for final ranking to the Merging Panel, which consists of all the topical panel Chairs plus a Merging Panel Chair. We made 29 offers until the 24 available positions were filled. Bios and photos of new 2024 NHFP Fellows were released along with a NASA press release on April 2.

The NHFP Science Leads and the diligent STScI Grants administrators (Shantavia Sturgis, Paula Sessa, and Bob Gicking) provide a re-

Figure 1: *Some of the fellows and science leads on the roof of 60 Garden Street after touring Harvard's Great Refractor during the September 2023 NHFP Symposium. Photo by Elias Aydi.*

mote orientation for new fellows each year in late March or early April to explain policies and benefits, to encourage communication among the fellows, and to answer any questions they may have.

The oversubscription of applicants to fellows may be intimidating. We urge anyone eligible to apply to consider that there is a strong diversity of science and backgrounds among successful applicants. Furthermore, our grading rubric rewards those applicants who have demonstrated "perseverance and determination along a path that may have been more difficult than usual." We particularly encourage applications from students with backgrounds traditionally underrepresented among professional astronomers.

As we pointed out last year, NHFP fellows now have an NHFP Mentoring and Outreach working group that makes public resources for applicants, including examples of previous NHFP applications, information on fellow-led postdoc application workshops, and feedback from current and former fellows on prospective fellows' application materials. The fellows also developed a graduate student mentorship program. Mentors—current and former postdoctoral fellows—provide professional and academic support and advice to astronomy-related researchers who are planning to write their first postdoc applications.

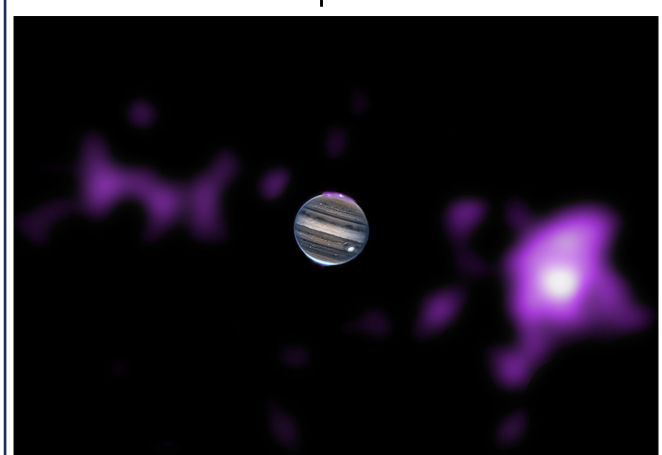
Other NHFP News

NASA has recently approved funding for fellows to use beyond just their scientific research, e.g., for efforts such as mentoring of students, public outreach, and career development. Guidelines for use of the funds are currently under development.

Remote work that was started during the pandemic has continued to be important for the program, allowing increased flexibility for several fellows that demonstrably enhances their personal and professional lives while keeping their research progress strong.

This article was prepared by Paul J. Green with input from the other NHFP Science Leads Andy Fruchter and Dawn Gelino, NHFP Lead programmer Megan Crane, and NASA NHFP Program Leads Antonino Cucchiara and Patricia M. Knezek.

Jupiter



Credit: X-ray: NASA/CXC/SAO; Infrared: NASA/ESA/CSA/STScl; Image Processing: NASA/CXC/SAO/J. Major, S. Wolk

Honoring and Celebrating 25 Years of *Chandra*

Kimberly Arcand & Megan Watzke

For those of us involved with the *Chandra* X-ray Observatory, this year marks a special milestone: twenty-five years ago, on July 23, 1999, the Space Shuttle Columbia launched *Chandra* into space, starting a quarter century of excellence and exploration.

With the 25th anniversary on the horizon, we have been planning projects over the past months and years to help celebrate this achievement. While the recent budget news has been disheartening, we are nevertheless persisting in trying to highlight all of the science *Chandra* has already accomplished—and will hopefully still achieve in the future.

This article highlights some of the public-facing projects for *Chandra*'s 25th anniversary. There are even more efforts aimed at the scientific community—ranging from colloquia at universities across the world to the *Chandra* 25th symposium in December 2024—that will be discussed elsewhere. A full list of events, including those aimed at scientists, is at https://cxc.harvard.edu/cdo/chandra25/.

We hope that the projects below will help those outside the mission and the field gain some understanding and appreciation of all that *Chandra* can do.

Astronomy on Tap: April–December 2024

Astronomy on Tap (AoT) is a network of outreach events focused on engaging talks on space and astronomy for general audiences, typically held in the social atmosphere of pubs and restaurants. Several AoT venues around the country have hosted and will host *Chandra* 25th anniversary themed events, ranging from Boston, Los Angeles, and New York City to Baton Rouge, Nashville, and Pittsburgh. In addition, international AoT satellite locations including Groningen, The Netherlands, and Paris, France, have also answered the *Chandra* 25 call, and even more satellites are expected to join as the year progresses. Keep an eye on the AoT events page to see if any *Chandra* talks are coming to your town.

Red Sox STEM Day: June 5, 2024

For several years, *Chandra* has been participating in the annual Red Sox STEM day. On June 5th, STS-93 Mission Specialist Cady Coleman joined the *Chandra* team for a day of baseball and black holes with a special video feature by Wally, the Red Sox mascot. With over 3,000 local students in attendance, CXC volunteers staffed a *Chandra* booth where they led educational activities and handed out anniversary materials. NESN, the Red Sox's television broadcaster, featured *Chandra* in a spot during the game, and an original video produced by *Chandra*'s Communications and Public Engagement (CPE) group was highlighted on Fenway Park's jumbotron during the event. There were talks in the morning including one by Kimberly Arcand on *Chandra* science and the headline talk on the STS-93 mission by Cady Coleman. That afternoon,

Cady Coleman spoke at Fenway Park as part of the Red Sox STEM day.

with *Chandra* staff cheering them on from right field, the Red Sox blew past Atlanta, 9–0.

Sphere: May–July 2024

Sphere is a fully-interactive cinematic venue next to the Las Vegas Strip that has been host to some of the biggest names in entertainment. On May 16, 2024, Sphere began a residency of Dead & Company of shows (that has since been extended into mid-August) featuring an unprecedented collaboration between Mickey Hart (drummer of Dead & Company and, formerly, the Grateful Dead) and *Chandra* data.

The collaboration, which arose after a friend of Mickey Hart attended a talk on *Chandra* sonification work by Kimberly Arcand at a Smithsonian event for the CfA, utilizes Sphere's 16k wraparound screen to display artistic versions of *Chandra* and multiwavelength imagery. Sonifications of the *Chandra* data inspired the Dead & Company's improvisational "Drums and Space" segment, the first time such sonified data have been worked into original live performances at this magnitude and the first time NASA/Smithsonian data have been projected on Sphere. Over 500,000 audience members will experience the *Chandra* content by the end of the residency.

Chandra in Washington, D.C.

Beginning in June, the inside of the lobby of NASA Headquarters featured an exhibit with information and images about *Chandra* and its twenty-five years of science. Then, starting mid-July, *Chandra* images are featured in 6 stops of the Washington, D.C. metro system: L'Enfant Plaza, Gallery Place, Metro Center, NoMa–Gallaudet U, Crystal City, and Farragut North stations. Approximately 500,000 riders are expected to pass through these stations during the time frame the *Chandra* images will be in place.

Summer Solstice Events at Smithsonian: June 22, 2024

The summer solstice gives the Smithsonian an opportunity to open its doors early and stay up late during its annual "Solstice Saturday." This year *Chandra*'s 25th anniversary was featured as a special theme in the activities around this day and night on the National Mall.

There was a *Chandra* booth at the "Astronomy on the Mall" event, where four SAO scientists and educators, including *Chandra*'s Ro-

Credit: NASA/CXC/K.Arcand

dolfo Montez Jr. and Rutuparna Das, engaged with thousands of members of the public. The booth showcased *Chandra* science from exploded stars to black holes and exhibited sonifications, 3D prints, augmented reality experiences, handouts, and activities celebrating *Chandra*'s 25th anniversary. At the Smithsonian's Hirshhorn Museum, Kimberly Arcand introduced a world-premiere screening and panel discussion on the new *Chandra* documentary on sonification, *Listen to the Universe* (streaming on NASA+). In the National Air and Space Museum, *Chandra* sonifications were shown in the planetarium, events included *Chandra* material on women in STEM, and the museum featured *Chandra*-focused trivia, scavenger hunts, and handouts. And over at the Smithsonian's National Museum of Natural History, *Lights Out*, the current exhibit on light pollution, features *Chandra* content, as well. All told, over 70,000 people attended the events that day where *Chandra* content was featured.

US Space & Rocket Center: August 23, 2024

Credit: Smithsonian

A panel discussion including STS-93 Commander Eileen Collins and *Chandra* scientists will be held in the planetarium at the US Space & Rocket Center (USSRC), down the road from the Marshall Space Flight Center in Huntsville, Alabama, in celebration of *Chandra*'s 25th anniversary. This event will be open to the public and include a *Chandra*-themed planetarium show directed by the USSRC, which will also be broadcast online.

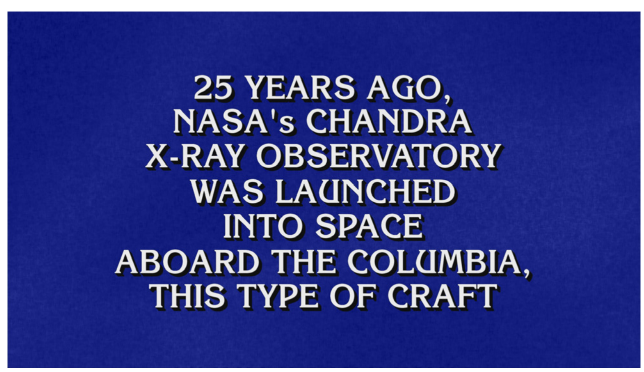
National Air and Space Museum lecture: September 25, 2024

The annual John H. Glenn Lecture in Space History will feature a moderated discussion about *Chandra* with *Chandra* scientists Patrick Slane and Kimberly Arcand and STS-93 crewmembers Eileen Collins and Cady Coleman.

This annual event is a signature lecture series for the National Air and Space Museum

Online, In Press, and on TV

In addition to the events above, the CPE team has also collaborated on and led a slew of *Chandra* 25th products. These include an educational insert in USA Today featuring *Chandra* content that appeared on April 7th and was sent to over 1.3 million print subscribers, a Smithsonian *Sidedoor* 2-episode podcast on *Chandra* and black holes released June 5th (parts one and two), an Apple Maps guide (location-based storytelling) for *Chandra* that de-



Credit: Sony Studios

buted in March, and a special reissue and new LP vinyl album of *Chandra* sonifications called *Universal Harmonies*, which can be found on bandcamp. In April, special augmented reality 3D Instagram experiences (also known as filters) of *Chandra* data were released, the first 3D Instagram experiences to also incorporate data sonifications, reaching over 2 million people. In June, *Chandra* was included as a clue on the TV game show *Jeopardy!*, reaching about 9 million viewers.

Throughout the year, there will be press releases that highlight different aspects of the quarter century of *Chandra* science. For example, in April, two stunning time-lapse movies of Crab Nebula and Cassiopeia A data collected over nearly two decades were released. In July, there was a special release of twenty-five new *Chandra* images coinciding with the anniversary of launch. And, timed with the First Light anniversary, three new sonifications will be released in August.

These are just a portion of the activities and materials celebrating *Chandra*'s 25th anniversary; for more, please visit https://chandra.si.edu/25th.

We hope you will join or have joined some of these events—or celebrate in your own way—as we celebrate this remarkable telescope and all that it has done for the past quarter century.

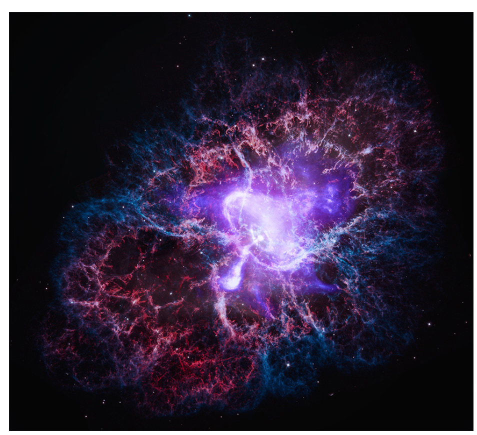
Arp 220

Credit: X-ray: NASA/CXC/SAO; Optical: NASA/ESA/STScI; Infrared: NASA/ESA/CSA/STScI; Image Processing: NASA/CXC/SAO/L. Frattare, J. Major

NGC 1365

X-ray: NASA/CXC/SAO; Optical: ESO/VLT; Infrared: NASA/ESA/STScI/JWST/PHANGS; Image Processing: NASA/CXC/SAO/L. Frattare, J. Major

Crab Nebula



Credit: X-ray: (Chandra) NASA/CXC/SAO, (IXPE) NASA/MSFC; Optical: NASA/ESA/STScI; Image Processing: NASA/CXC/SAO/J. Schmidt, K. Arcand, and L. Frattare