Astrophys Space Sci
DOI 10.1007/s10509-006-9193-x

The Chandra X-ray Observatory: An Astronomical Facility Available to the World

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Received: 2 May 2006 / Accepted: 2 June 2006

Abstract The *Chandra* X-ray observatory, one of NASA's "Great Observatories," provides high angular and spectral resolution X-ray data which is freely available to all. In this review I describe the instruments on *chandra* along with their current calibration, as well as the *chandra* proposal system, the freely-available *chandra* analysis software package CIAO, and the *chandra* archive. As *chandra* is in its 6th year of operation, the archive already contains calibrated observations of a large range of X-ray sources. The *chandra* X-ray Center is committed to assisting astronomers from any country who wish to use data from the archive or propose for observations.

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Keywords

1. Introduction

The *Chandra* X-ray Observatory (Weisskopf et al., 2000) was launched on the Space Shuttle Columbia as part of STS-93 and deployed on July 23, 1999, after over 20 years of planning and development. *Chandra* was designed to be a general-purpose X-ray observatory, with a specific focus on high-resolution imaging and spectroscopy. *Chandra's* mirrors resolve objects smaller than 1", a level comparable to optical telescopes and significantly better than any previous X-ray observatory.

Chandra is one of NASA's "Great Observatory" missions, along with the Hubble Space Telescope, the Compton Gamma Ray Observatory, and the Spitzer Space Telescope. To maximize the scientific return from each of these missions, NASA created a science center for each mission which would be responsible for coordinating calibration efforts for all instruments, organizing proposals for the telescope, developing software to analyze the data returned, and maintaining the mission archive. The *Chandra* X-ray Center (CXC) is located in Cambridge, Massachusetts and has a team of scientists handling all of these duties.

2. Observatory specifications

Chandra, like the Hubble Space Telescope, was launched into orbit in the Space Shuttle. Unlike the Hubble Space Telescope, after being deployed *Chandra* used a secondary rocket to boost it into a highly elliptical orbit. Currently, *Chandra*'s apogee is ~139,000 km above the Earth (1/3 of the distance to the Moon), well outside the Earth's radiation belts, and its perigee is ~16,000 km, well within them. This elliptical orbit put it out of reach of any maintenance mission, but allows continuous observing for over 100 ksec (observations cannot be done within or near the radiation belts). As a result, *Chandra* regularly achieves an observing fraction of nearly 70%, extremely high for satellite observations.

2.1. Mirrors

The *Chandra* High Resolution Mirror Assembly (HRMA) is responsible for its sub-arcsecond imaging. The HRMA consists of four pairs of nested mirrors in a Wolter Type-I design. The mirrors are made of iridium-coated glass, and the entire system has a focal length of 10.07 meters. The unobstructed geometric effective area is 1145 cm^2; in flight the total effective area is 800 cm^2 at 0.25 keV, 400 cm^2 at 5 keV, and 100 cm^2 at 8 keV. The ghost-free field of view has

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a $30'$ diameter, which encompasses the entire ACIS detector array and most of the HRC (see below for details about the *Chandra* detectors).

The primary differences between *Chandra* and *XMM-Newton* (Gabriel, Guainazzi and Metcalfe, 2005) are found in their mirrors. *XMM-Newton* has three X-ray telescopes, each with 58 nested gold-coated nickel shells, while *Chandra*'s single HRMA has only 4 mirror pairs made of precisely formed iridium-coated glass. As a result, *XMM-Newton* has a larger effective area than *Chandra*, but worse angular resolution.

The HRMA was calibrated at the NASA/Marshall Space Flight Center X-ray Calibration Facility pre-flight, and these measurements have been used to cross-check the in-flight calibration with excellent results. More information about the HRMA and the latest calibration can be found at `http://cxc.harvard.edu/cal/Hrma`.

2.2. ACIS

The Advanced CCD Imaging Spectrometer (ACIS) (Garmire et al., 2003) is the most-used detector on *Chandra*. Unlike *XMM-Newton*, *Chandra* has only a single HRMA and the observer must chose the detector to put into the focal plane. The ACIS is a set of 10 CCDs arranged in two patterns: a 2 × 2 array with a $17'$ square field of view used primarily for imaging, and a 1 × 6 array with a $8.5' \times 51'$ field of view, used primarily for grating observations. The user can select up to 6 CCDs to be used for any observation (the 6 CCD limit is set by the power available from the solar panels). The CCDs are operated in single-photon counting mode, which provides modest ($E/\Delta E \sim 50$ spectral resolution) and limited timing information.

The ACIS contains 8 'front-illuminated' (FI) and 2 'back-illuminated' (BI) CCDs. The FI CCDs have their gate structures mounted facing the mirrors, while the BI CCDs are inverted. As a result, the BI CCDs have larger effective area at low energies since no X-rays are lost in the gate structures. However, they also have higher backgrounds and initially lower spectral resolution. However, early in the *Chandra* mission, protons from the Earth's radiation belts damaged the FI CCDs with the result that the FI CCD resolution now varies strongly with CCD row number. The CXC has developed algorithms to partially correct this effect as part of CIAO (see Section 3.3).

The pixel size of the ACIS CCDs is $0.492''$ on a side; as a result the ACIS barely samples the full HRMA resolution. To reduce the effect of pixel-to-pixel calibration uncertainties, and to avoid damaging the on-axis pixels, *Chandra* dithers in a $16''$ lissajous pattern during all ACIS observations. A separate instrument using an optical CCD called the Aspect Camera is used to point *Chandra* and to remove the effect of dither from the final images and event files. The reduction is handled by the CXC as part of the standard pipeline analysis (see Section 3.2). For more information about the ACIS, please see `http://cxc.harvard.edu/proposer/POG/html/ACIS.html`.

2.3. HRC

The High Resolution Camera (HRC) (Murray et al., 2000) instrument consists of two microchannel plate detectors. The HRC-I is designed for imaging and has a $30'$ square field of view, while the HRC-S is designed to be used with LETG grating (see Section 2.5) and has a $6' \times 99'$ field of view. As these are microchannel plate detectors, they have no useful energy resolution but do have better timing and a smaller pixel size than the ACIS detectors. In addition, they do not suffer from photon pileup as happens in CCD detectors when the event rate becomes large.

Although the intrinsic timing accuracy of the HRC detectors is 16μs, in flight the actual event timing is known to approximately 4 ms due to a wiring error. However, it is possible in special cases to regain the 16μs accuracy using a special instrument mode. For more information about the HRC, please see `http://cxc.harvard.edu/proposer/POG/html/HRC.html`.

2.4. HETG

In addition to the two detectors, *Chandra* has a two different grating assemblies that can be inserted, although only one can be in place at any given time. The High Energy Transmission Grating (HETG) (Canizares et al., 2000) was designed to be used with the ACIS-S detector, although it could be used with ACIS-I or the HRC (in practice this is not useful for scientific observations). The HETG itself contains two different gratings, the High Energy Grating ($\Delta\lambda = 0.012$Å) and the Medium Energy Grating ($\Delta\lambda = 0.023$Å). These two gratings are arranged so that their dispersion axes are angled ~10° from each other, so that both dispersed spectra can be independently extracted. The HEG spectral range is 1.2–15Å(0.8–10 keV), while the MEG spectral range covers 2.5–31Å(0.4–5 keV). The HEG has twice the resolution of the MEG, balanced by a smaller effective area.

Unlike the *XMM-Newton* RGS, the *Chandra* gratings lose resolution quickly for sources larger than a few arcseconds. For point sources, however, the HETG combines high spectral resolution with sufficient effective area to measure spectra from both Galactic and extragalactic sources.

The HETG has significantly overlapping orders, but these can be easily separated using the energy resolution of the ACIS-S CCDs. By design, the HETG suppresses the even order peaks in order to maximize the first order intensity; for bright sources, the 3rd order spectrum can be used and provides even higher resolution. For more information about the HETG, please see `http://cxc.harvard.edu/proposer/POG/html/HETG.html`.

2.5. LETG

The Low Energy Transmission Grating (LETG) (Predehl et al., 2000) complements the HETG, providing high resolution spectra of point sources in the range 1.2–175Å(0.07–10 keV). Unlike the HETG, the LETG has only a single grating, with resolution $\Delta\lambda = 0.05$Å. The LETG can be used with either the HRC or the ACIS. The HRC-S is needed in order to get the wide spectral coverage out to 175Å, but the data are then limited by the lack of energy resolution and the relatively high background in the HRC-S. As a result, a number of observations have been done using the LETG in combination with the ACIS-S detector. When used with the ACIS-S, the spectral range decreases to 1.2–65Å. However, by design, this arrangement maximizes the effective area and resolution around the prominent O VII and O VIII lines around 19–22Å. In addition, in flight the ACIS-S has about 1/4th the background of the HRC-S.

Overlapping orders is also an issue with the LETG. When used with the HRC-S, which has no intrinsic energy resolution, the orders cannot be resolved directly. As a result, they have to be determined iteratively (if possible) or simply modeled. Unlike the HETG, orders up to $m = 10$ can contribute to the final result, so in many situations this issue must be addressed carefully. For more information about the LETG, please see `http://cxc.harvard.edu/proposer/POG/html/LETG.html`.

3. The Chandra X-ray center

The *Chandra* X-ray Center (CXC) is responsible for operating *Chandra* and maximizing its scientific output. This includes scheduling, operations, calibration, software development, and data archiving, as described below.

3.1. Proposals

The CXC issues a call for proposals once per year, with proposals usually due sometime in March. Proposals are welcomed from any astronomer regardless of country, and are evaluated by an independent international group of astronomers. A complete description of the information needed for a proposal can be found at `http://cxc.harvard.edu/proposer/POG/index.html` and is also available in hardcopy.

Once a year's list of targets has been selected, the CXC mission operations team sorts the targets into a long- and short-term schedule. The principal investigator for each observation is contacted to confirm the final settings for the observation, and then it is passed to the Operations Control Center (OCC), also located in Cambridge, MA at MIT to be uploaded to the satellite. Uploads are done approximately once per day via NASA's Deep Space Network; unscheduled or continuous contacts are available as needed. This, along with the need to have 3 days worth of observations uploaded at all times, limits *Chandra*'s ability to respond to a Target of Opportunity request; in most cases a 24–48 hour response is the best possible.

3.2. Calibration

The CXC calibration team both collects calibration data from the individual instrument teams (ACIS, HRC, HRMA, LETG & HETG) and reduces calibration data itself. Calibration data is regularly obtained from set-aside time to both track *Chandra*'s performance and to address new needs as they arise. For example, the SNR E0102 is regularly observed to track the ACIS effective area, while the star AR Lac was observed with the HRC-I to measure the HRMA PSF.

Complete information about the current calibration status is available at `http://cxc.harvard.edu/cal`. Currently, *Chandra*'s absolute positioning is known to 0.6″ while relative positions are known to 0.1″. Effective areas for the different detectors are known to 10–20%, while the energy resolution is known to 4–5%.

There is a yearly calibration workshop held in Cambridge, MA, where the latest calibration work is presented and the entire team is available for questioning. The proceedings of these meetings are also listed on the above website.

The work of the calibration group is compiled in the calibration database (CALDB), which is used by the *Chandra* data pipeline and the analysis software.

3.3. CIAO

The *Chandra* Interactive Analysis of Observations (CIAO) software package is comprehensive package of *Chandra* data reduction and analysis tools. CIAO was written by professional programmers at the CXC, working under the direction of X-ray astronomers to develop software that would (a) process data from *Chandra* into calibrated event lists, images, and spectra and (b) allow users to analyze these data easily. The entire CIAO package is freely available both as source code and precompiled for a range of computer platforms, including Linux, OS X, and Solaris. System requirements are relatively modest, and useful work can be done with a 300 MHz machine with 256 MB of RAM and 5 GB of disk space. If needed, the CXC will mail a CD containing CIAO (and the CALDB) anywhere in the world.

CIAO contains over one hundred individual programs to perform various operations. However, to guarantee uniformity of interface and application, almost all of these tools use the same set of code libraries. One such library is the "Data Model" (DM), which CIAO tools use to access the raw data files. In practice, tools that use the DM allow users to filter event data "on-the-fly," selecting only particular regions or times of interest for any individual process, such as creating a lightcurve or extracting a spectrum. Many CIAO tools also use a standard parameter interface library, similar to that used by the IRAF package. Recently, the CIAO developers have incorporated the S-lang scripting language (see `http://www.s-lang.org` for more information about S-lang) into some CIAO tools and developed S-lang interfaces to many CIAO libraries. This allows users to easily develop their own CIAO tools which access the same libraries as official CIAO tools. These can be submitted to the CXC for general use (and in some cases official incorporation into CIAO) at the website `http://cxc.harvard.edu/cont-soft/soft-exchange.html`.

CIAO is extensively documented both on the CXC website (`http://cxc.harvard.edu/ciao`) and within CIAO itself via the `ahelp` command, which returns a description for every CIAO command as well as a large number of CIAO terms (e.g. `ahelp dmfiltering` for information about using DM filters). In addition, the website also contains "threads" with step-by-step descriptions of common tasks as well as "why threads" describing *why* particular tasks are needed. An active helpdesk is also supported where CIAO experts will answer questions submitted via email or a web interface. Approximately twice per year, 2–3 day CIAO workshops are held where CXC scientists describe how to reduce X-ray data using CIAO and users can get hands-on experience with immediate assistance from these experts.

3.4. Archive

All *Chandra* observations are stored in the *Chandra* archive, in a number of formats ranging from very nearly the raw telemetry to calibrated event lists, images, and spectra. Access to this data is determined by its purpose. Data taken for calibration is immediately available, while guest observer observations are generally restricted to the principal investigator for one year. *Chandra*'s Director has a pool of timediscretionary available for unexpected opportunities; these data are also immediately available to all.

Access to the archive is normally done via the Internet, using either the standalone "chaser" java applet or the web interface "webchaser" available at `http://cda.harvard.edu/chaser/main Entry.do`. The main archive is stored at the CXC in Cambridge, but a mirror site is also available in the UK at the University of Leicester. *Chandra* datasets vary in size from ~ 50 MB to over 2GB, depending on the detector used, the source flux, and the length of the observation. If network speed is a limiting factor, a CD-ROM can be made at the CXC and sent to the user.

4. Conclusions

Chandra's launch opened the new era of X-ray astronomy, adding capabilities in the X-ray that could finally match optical telescopes in angular and spectral resolution. The open proposal process allows any astronomer to use *Chandra*'s capabilities, and the relatively modest computing requirements combined with the open archive allow relatively easy access to *Chandra* datasets. The CXC has actively supported the COSPAR X-ray astronomy schools in the past, and remains committed to supporting the use of *Chandra* around the world.

Acknowledgements The author worked at the CXC from launch until May 2004 when he moved to his current position working with the Astro-E2 mission, to be launched in 2005. The article was not reviewed by the CXC and does not, therefore, represent the official CXC position on any issue.

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